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Molecular Tools for Biotechnological Applications in Aquatic Ecosystems: Use in Toxic Studies, Bioindicators, Biomarkers, and Culture-Independent Techniques

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Aquatic ecosystems are increasingly affected by pollution, which threatens their biodiversity and health. Traditional monitoring methods detect pollutants but do not fully explain their biological impacts. Molecular tools such as PCR, genomics, and omics technologies provide deeper insights into how pollutants affect aquatic organisms at the genetic and cellular levels. These tools are useful in toxicological studies, as well as in identifying bioindicators and biomarkers for early detection of environmental stress. Culture-independent techniques further help in studying microbial diversity without the need for laboratory cultivation. Overall, molecular approaches offer a more accurate and efficient way to monitor and manage aquatic ecosystems.

1. Introduction

Aquatic ecosystems are very important for maintaining ecological balance and supporting biodiversity. However, they are highly sensitive to pollution from industrial discharges, agricultural runoff, and domestic waste (Sharma & Singh, 2020). These pollutants include heavy metals, pesticides, plastics, and organic waste, which can accumulate in water bodies and harm aquatic life. Earlier, environmental monitoring mainly depended on chemical analysis of water. While this helps identify pollutants, it does not show how living organisms are affected. Molecular tools have changed this approach by allowing scientists to study changes at the DNA, RNA, and protein levels (Verma et al., 2021). This gives a deeper understanding of how pollutants impact aquatic organisms. These tools are now widely used in toxicological studies, identification of bioindicators and biomarkers, and in studying microbial communities without the need for culturing them (Zhou et al., 2020).

2. Molecular Tools in Aquatic Biotechnology

2.1 PCR and qPCR

Polymerase Chain Reaction (PCR) is one of the most commonly used molecular techniques. It helps in amplifying small amounts of DNA so that they can be studied in detail (Mullis & Faloona, 1987). In aquatic ecosystems, PCR is used to detect microorganisms, harmful pathogens, and genes involved in pollutant degradation.

Quantitative PCR (qPCR) is an advanced form of PCR that measures the amount of DNA in real time (Kubista et al., 2006). This makes it possible to study how genes respond to pollution. For example, scientists can measure how stress-related genes increase when organisms are exposed to toxic substances (Smith & Osborn, 2009). These techniques are fast, sensitive, and can detect even very small changes, which makes them very useful in environmental monitoring.

2.2 Genomics and Metagenomics

Genomics is the study of the complete genetic material of organisms. It helps in understanding how genes function and how organisms respond to environmental stress. Metagenomics is especially important in aquatic ecosystems because it studies genetic material directly from water or sediment samples (Handelsman, 2004). Many microorganisms in aquatic environments cannot be grown in the laboratory. Metagenomics helps in studying these unculturable microbes and understanding their role in nutrient cycling and pollutant degradation

(Riesenfeld et al., 2004). This approach has shown that microbial communities play a very important role in breaking down pollutants and maintaining ecosystem health (Tyson et al., 2004).

2.3 Omics Technologies

Omics technologies include transcriptomics, proteomics, and metabolomics. These approaches help scientists understand how organisms respond to pollution at different levels. Transcriptomics studies gene expression and shows which genes are active under stress conditions (Hasin et al., 2017). Proteomics studies proteins, which carry out most of the functions in cells. Changes in protein levels can indicate stress or damage caused by pollutants. Metabolomics studies small molecules and helps in understanding changes in metabolism (Bundy et al., 2009). Together, these techniques give a complete picture of how pollutants affect aquatic organisms.

2.4 Gene Editing Tools

Gene editing tools like CRISPR allow scientists to make precise changes in DNA (Jinek et al., 2012). In aquatic biotechnology, these tools are being used to develop organisms that can tolerate pollution or degrade harmful substances.

For example, certain bacteria can be genetically modified to break down oil spills or toxic chemicals more efficiently (Nielsen & Keasling, 2016). Although this field is still developing, it has great potential for improving environmental management.

3. Molecular Tools in Toxicological Studies

Toxicological studies aim to understand how pollutants affect living organisms. Molecular tools have made it possible to study these effects at a very detailed level. Pollutants can cause damage to DNA, proteins, and cell structures. They can also lead to oxidative stress, which affects normal cell function (Stoliar, 2011). By studying gene expression, scientists can detect early signs of stress even before visible damage occurs (Ankley et al., 2006). These tools also help in understanding how different levels of exposure affect organisms. This information is useful for setting environmental standards and protecting aquatic life (Van der Oost et al., 2003).

4. Bioindicators and Biomarkers in Aquatic Ecosystems

4.1 Bioindicators

Bioindicators are organisms that help us understand the condition of the environment. In aquatic ecosystems, fish, algae, plankton, and benthic organisms are commonly used as bioindicators (Holt & Miller, 2011).

These organisms are sensitive to pollution and show changes in behavior, growth, and reproduction when exposed to contaminants. They can also accumulate pollutants in their bodies, which helps in detecting contamination over time (Markert et al., 2003). For example, a decline in fish population or abnormal growth in algae can indicate pollution. Bioindicators are useful because they reflect the actual condition of the ecosystem.

4.2 Biomarkers

Biomarkers are measurable biological responses that indicate exposure to pollutants. These responses can occur at molecular, cellular, or physiological levels. Common biomarkers include DNA damage, changes in enzyme activity, and production of stress proteins (Stoliar, 2011). These changes can be detected using molecular tools.

Biomarkers are very useful because they can detect pollution effects at an early stage, before serious damage occurs (Van der Oost et al., 2003). This helps in taking preventive measures and protecting aquatic ecosystems.

5. Culture-Independent Techniques

Traditional microbiological methods require growing organisms in the laboratory, but many aquatic microorganisms cannot be cultured. Culture-independent techniques allow scientists to study

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these organisms directly from environmental samples.

Metagenomics and next-generation sequencing (NGS) are commonly used culture-independent methods (Shokralla et al., 2012). These techniques help in identifying microbial diversity and understanding their role in ecosystem processes. Studies have shown that a large number of microorganisms in aquatic ecosystems are unculturable, which makes these techniques very important (Stewart, 2012). They have greatly improved our understanding of microbial ecology and pollution processes.

6. Conclusion

Molecular tools have greatly improved the study of aquatic ecosystems and pollution. They provide detailed information about how pollutants affect organisms and help in early detection of environmental stress (Verma et al., 2021). The use of bioindicators and biomarkers gives a better understanding of ecosystem health. Culture-independent techniques have also helped in studying microbial diversity in a more effective way (Zhou et al., 2020).

In the future, combining different molecular approaches will help in better monitoring and management of aquatic ecosystems.

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Estimation of heritability and genetic advance of saltol in segregating rice (Oryza sativa L.) Genotypes through phenotypic characters.

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Salinity in soil poses a major challenge to crop production, especially in areas that depend on irrigation. At the Sokoine University of Agriculture in Tanzania, two rice genotypes (NERICA-L-19 and SUAKOKO-10) that are prone to salinity were crossed with a tolerant genotype to create F2 and F3 populations for studying heritability and genetic improvement across eight quantitative traits. The use of marker-assisted selection aided in the development and identification of these populations. A total of 192 F2 and 96 F3 populations, along with three parent lines and one susceptible check, were assessed using a randomized complete block design with four replications. The genotypic coefficient of variation (GCV) varied from 4.5% for the days to 50% flowering to 22.23% for the SES score, while the phenotypic coefficient of variation (PCV) ranged from 4.56% to 25.01% for the traits.

Heritability estimates ranged from 0.82 for the SES score to 0.98 for the number of days to reach 50% flowering. The genetic advance varied from 1.14 g for grain yield per plant to 13.87 cm for plant height. A high genetic advance was noted for plant height and days to 50% flowering, while reproductive tillers and spikelet sterility showed a moderate genetic advance. The lowest genetic advance values were found for grain yield per plant and 1000-grain weight. Elevated heritability estimates along with high expected genetic advance for plant height and days to 50% flowering indicate that phenotypic selection for these characteristics will be effective. Positive correlations were found among yield and its components. Grain yield exhibited a significant positive correlation with 100-grain weight and the count of reproductive tillers, suggesting that these characteristics are appropriate selection criteria for enhancing yield in future generations. In summary, heritability, genetic progress, and favorable trait relationships are advised as selection criteria for the improvement of rice genotypes.

5.Introduction

Rice, scientifically known as Oryza sativa (Asian rice) and Oryza glaberrima (African rice), is an essential food crop and a primary staple for a significant portion of the global population (Zhao et al., 2011). It accounts for approximately 21% of the world's human per capita energy and provides 15% of per capita protein and calories. In Asia, rice is particularly important, especially among impoverished communities, as it contributes to 50-80% of their daily caloric intake (IRRI, 2001). However, rice is highly susceptible to saline conditions, which restricts its production (Naheed *et al.,* 2008; Shahbaz and Zia, 2011).

Enhancing salt tolerance in rice is an essential strategy to combat abiotic challenges, especially salinity stress. According to Abebe *et al.* (2017), genetic diversity in rice is vital for creating an effective rice breeding program.

Heritability is a central factor determining the effectiveness of selection, as it predicts how much genetic gain breeders can expect in selected traits. By estimating heritability and genetic advance, breeders can better forecast improvements from selection and

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choose suitable breeding methods (Tiwari, 2015; Johnson et al., 1955; Falconer, 1981). These tools guide plant breeders in selecting elite genotypes from diverse genetic populations, since genetic advance specifically quantifies the gain achieved through selection by considering variability, heritability, and selection intensity.

5.1 Materials and Methods

5.1.1 Study location

The study was conducted at the Chanzuru irrigation scheme in Kilosa District, Morogoro Region, but water samples were collected from both the Chanzuru and Ilonga irrigation schemes to compare the quality of irrigation water because the two schemes have one common source of water; moreover, farmers at both schemes have reportedly experienced salinity problems in their fields. Kilosa District is located approximately 300 km inland from the coast of Tanzania. Kilosa is also one of six districts within the Morogoro region. It is 14,245 km2 in size, making up about 20 per cent of the region (KDC, 2010). The district lies between 6°S and 8°S, and 36°30'E and 38°E. It borders the Tanga Region to the north and the Morogoro District to the East. In the South, it is bordered by the Kilombero District and part of the Iringa Region (KDC, 2000). Kilosa District is comprised mostly of flat lowland that covers the whole of the eastern part, which is called the Mkata Plains.

5.1.2 Experimental design

In April 2016, forty-eight seeds from each rice family (F3 and F2) were planted following the crosses NERICA-L-19 x FL 478 and SUAKOKO-10 x FL 478. This planting included a susceptible check variety (IR 29) and parent materials. The NLF2 & NLF3 seeds were selected based on grain weigh and spikelet sterility. The experiment was designed as a randomized complete block design (Kalton, 1948; Mishra et al., 2003; Zdravković et al., 2011; Nakhaei *et al.,* 2014; Menezes-Júnior *et al*., 2016; Liu *et al.,* 2016) with four replications. Each replicate consisted of one row measuring 3.25 meters, with a plant spacing of 25 cm x 25 cm and 50 cm between each replicate. Borders were planted with the FL478 rice variety. The field conditions included sandy clay with low exchaneageble sodium percentage (ESP), irrigated via the use of a canal, and fertilized using NPK (15-15-15) and nitrogen-rich fertilizer.

Breeding scheme for the development of rice (*Oryza sativa*, L) genotypes

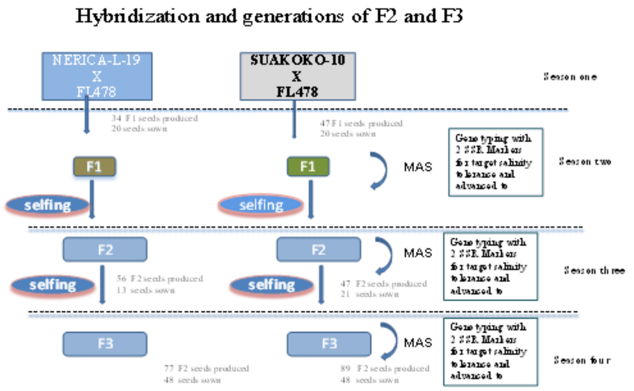

Figure 1: Marker assisted selection breeding adapted for the introgression of salt tolerance markers into improved genetic bases

2.0 Soil and Water Sampling and Analyses

Prior to the experiment, four composite soil samples were collected from the site, specifically from the top 30 cm of soil at each plot's corners and center. The samples were air-dried, and soil solutions were prepared by mixing the soil with water in a ratio of 1:2.5 (soil to water). These solutions were analyzed for the following parameters: sodium (Na^+), magnesium (Mg^{2+}), potassium (K^+), calcium (Ca^{2+}), organic carbon (OC), total nitrogen (TN), phosphorus (P), pH, and electrical conductivity (EC).

Total nitrogen was measured using the Kjeldahl method, while organic carbon was determined via the Walkley-Black method. Exchangeable phosphorus was quantified using the Olsen method, and the levels of available potassium, sodium, magnesium, and calcium were assessed with the ammonium acetate extraction method. Soil pH was measured with a

Hanna Instrument pH Meter (Model Hi 9032) using a 1:2.5 soil-to-water ratio. Additionally, electrical conductivity was recorded with a Hanna Instrument Conductivity Meter (Model Hi 9032), also using a 1:2.5 soil-to-water ratio (Jackson, 1973).

Water samples were collected from the Chanzuru and Ilonga irrigation schemes prior to the study. These samples included water from the Main River, the experimental site, the irrigation pond, and nearby wells. The samples were analyzed for calcium, magnesium, and sodium content. Sodium levels were measured using a flame photometer, while calcium and magnesium concentrations were determined with an atomic absorption spectrophotometer.

2.1 Data collection

The rice genotypes were evaluated based on eight quantitative variables representing the reproductive and ripening growth stages. The standard evaluation score (SES) followed the method by Gregorio *et al.* (1977), and trait selection and measurement techniques were based on the IRRI standard evaluation system of rice (IRRI, 1980).

Panicle length was measured in centimeters from the base of the plant to the tip of the panicle, while plant height was recorded in centimeters from the base of the shoot to the tip of the tallest leaf blade. Spikelet sterility readings were obtained by counting well-developed spikelets in proportion to the total number of spikelets of five panicles.

The 100-grain weight was determined from a random sample of 100 well-developed, whole grains within a population, dried to 13% moisture content, and weighed on a precision balance. Reproductive tillers were considered those tillers that produced spikelets with or without filled grains and were counted for all genotypes.

The number of tillers was considered as the number of shoots that grew after the initial parent shoot. Days to 50% flowering was determined as the number of days from sowing to when 50% of the rice population had flowered, and grain yield was considered as the average weight of filled grains on five panicles per plant.

Plants were scored based on the IRRI standard evaluation of salinity injury, and data were collected on five plants per hill and averaged for data analysis.

To assess and quantify the genetic variability among the genotypes, the variance components and values of heritability and genetic advance were estimated using the formula given by Burton and De Vane (1953) and applied by many researchers such as Johnson *et al.* (1955), Fehr *et al.* (1987), Allard (1999); Baye (2002), Tuhina-Khatun*et al.* (2015) among others. $Vg = (MSG\text{-}MSE/r)$; $Vp = (MSG/r)$; $Ve = MSE/r)$;

Where MSG is the mean squares of genotypes, MSE is the mean squares of error, and *r* is the replication.

The coefficients of variability, both genotypic (GCV) and phenotypic (PCV), were computed using the following formulas: $PCV = (\sigma p/M) \times 100$ and $GCV = (\sigma g/M) \times 100$. In these formulas, σg and σp represent the genotypic and phenotypic standard deviations, respectively, while M stands for the grand mean of the trait.

Furthermore, heritability in the broad sense (h2) was determined based on genotypic means using the formula $h2 = Vg/Vp$, where h2 signifies heritability, Vg denotes genotypic variance, and VP represents phenotypic variance.

The genetic gain (GA) was estimated using the formula $GA = k\sigma p.h^2b$.

Where *k* is selection intensity in standard units. Five percent (5%) of F2 and F3 were selected to produce the populations of the next generations, and k=2.06, h^2b broad sense heritability; σp = the phenotypic standard deviation estimated as the square root of the variance.

2.2 Data analysis

All gathered data for the traits were evaluated using the Genstat statistical package version 14, and the means of the traits were differentiated through the Tukey Honestly Significant Difference (HSD) test.

3 Results and Discussion

Weather data, soil, and water properties

The weather data collected throughout the experiment indicated minimum and maximum temperatures of 18.27°C and 29.64°C, respectively (see Table 1).

Table 1: Weather information during the experiment

Weather information			
	Temperature °C		
Month	**Minimum**	**Maximum**	**Rainfall (mm)**
March	22.8	34.1	7.24
April	21.4	29.9	21.6
May	18	28.8	14.1
June	16.2	27.8	2.2
July	15.3	28.3	2
August	16.6	28.9	5.3
September	17.6	29.7	2.6
Average	**18.27**	**29.64**	**7.86**

The soil analysis presented in Table 2 revealed that the chosen experimental location was completely saline. The electrical conductivity (ECe) readings ranged from 4.98 to 6.78 dS/m, with a pH that fell between 7.43 and 7.74. The soil exhibited a sandy-clay composition with a significant clay content, which inhibited water drainage. The exchangeable sodium percentage (ESP) ranged from 5.4% to 12%, indicating that the soil is saline but not sodic. An ESP value of 15% or lower signifies saline soils, while an ESP above 15% indicates sodicity. Generally, saline soils have an ESP of less than 15% and an electrical conductivity greater than 4 dS/m, while sodic soils are characterized by an ESP greater than 15% and an electrical conductivity of less than 4 dS/m at 25°C (U.S. Salinity Laboratory Staff, 1954).

Table 2: Soil analysis

Ece		EC	Particle size density			Texture	TN (Kjeld)	OC (BlkW)	Ex. P (mg/kg)	CEC (cmol/kg)	zinc	Copper	Exchangeable bases (cmol/kg)				ESP
Lab. Nos	pH	(dsm-1)	% cla y	% silt	% sand	Class	%	%	Pbry-1	CEC	mg/kg	mg/kg	Ca_{2+}	Mg_{2+}	K_{+}	Na_{+}	(%)
BLOCK I	**7.74**	**4.98**	**38.32**	**3.28**	**58.4**	**Sandy clay**	**0.1**	**0.98**	**13.97**	**15**	**1.53**	**6.87**	**6.49**	**7.88**	**0.4**	**0.81**	**5.4**
BLOCK II	7.43	6.57	40.32	3.28	56.4	Sandy clay	0.11	1.19	16.14	16	1.14	7.34	12.8	9.94	0.4	1.82	11.4
BLOCK III	7.53	6.48	41.31	2.29	56.5	Sandy clay	0.12	0.87	19.79	18.2	1.64	7.45	5.2	10.42	0.6	2.18	12
BLOCK IV	7.61	6.78	38.35	5.38	56.3	Sandy clay	0.11	1.19	24.25	17.3	1.06	7.34	6.08	9.65	0.5	1.5	8.7

The soil sample examined from the experimental site revealed an average ECiw of 6.20 dsm-1, and Fig. 2 documents the soil's appearance during the experiment.

ISSN: 3049-2289

Fig. Appearance of soil at experimental site in Chanzuru, Kilosa

4 Genetic Parameters for Agronomic Characters of Rice Generations

The information shown in Table 3 includes genetic advance (GA), heritability (h2b), phenotypic variance (Vp), genotypic variance (Vg), phenotypic coefficient of variation (PCV), and genotypic coefficient of variation (GCV). An intriguing discovery is that for every trait, the PCV was consistently greater than the matching GCV, indicating a significant interaction between the environment and all traits. Furthermore, for every character, the components of phenotypic variance (σ2p) were consistently higher than the components of genotypic variance (σ2g), suggesting that environmental influences have an impact on how these traits are expressed. The very minor variations between PCV and GCV imply a minimal environmental impact, despite the fact that this influence was noteworthy.

Understanding genetic variation is essential in breeding programs for selecting desirable agronomic traits. High heritability was observed for days to 50% flowering (98.0%), plant height (96%), panicle length (88%), spikelet sterility (853%), reproductive tillers (85%), salinity injury (82%), and number of tillers (56%). As Johnson et al. (1955) noted, both heritability and genetic advancement are key to achieving significant improvements through selection. Plant height (13.87 cm) and days to 50% flowering (8.97 days) demonstrated high genetic advances and heritability. These results suggest strong potential for effective selection, especially for yield improvement.

Certain traits, including spikelet sterility (4.7%), reproductive tillers (3.54), SES score (2.08), panicle length (2.35 cm), 100-grain weight (1.15 g), and grain yield per plant (1.14 g), showed high heritability but moderate to low genetic advance. Selection for these traits may therefore be less effective than for traits with both high heritability and high genetic advance. The low heritability and genetic advance for the number of tillers indicate a strong environmental influence.

Table 3: Genetic parameters for agronomic characters of four rice generations

Traits	Vg	Vp	GCV%	PCV%	h^2_B	GA
Days to 50% Flow. (days)	19.1	19.82	4.5	4.56	0.98	8.97
100-grain weight (g)	0.33	0.35	13.1	23.4	0.94	1.15
Grain yield (g/plant)	0.37	0.44	11.12	12.19	0.83	1.14
Panicle length (cm)	1.49	1.7	6.16	6.56	0.88	2.35
Plant height (cm)	47.3	49.35	10.43	10.65	0.96	13.87
Reproductive tillers (#)	3.5	4.14	13.05	14.19	0.85	3.54
SES Scores (scale)	1.25	1.53	22.23	25.01	0.82	2.08
Spikelet sterility (%)	6.27	7.54	15.11	13.81	0.83	4.70
No. of Tillers	1.6	2.88	6.74	9.05	0.56	2.00

Selection intensity (5%) = 2.06; Ve = Environmental variance, GCV Genotypic coefficient of variation, PCV Phenotypic coefficient of variation, Vp = phenotypic variance, genotypic variance, GA Genetic advance/Genetic gain.

5 Analysis of Variance and Mean Performance of Rice Genotypes under Saline Conditions

A significant level of genetic variability among the genotypes was shown by the analysis of variance (ANOVA), which showed a highly significant mean square owing to genotypes (Table 4). Plant height (197.34 cm) showed the highest genotypic variability, followed by spikelet sterility (31.11%), days to 50% blooming (79.28), reproductive tillers (25.95), and panicle length (20.0 cm). On the other hand, panicle length (6.79 cm), SES scores (6.64), grain output per plant (1.85g), and 100-grain weight (1.38g) all showed low genetic variability. These results are in line with those of Jahan et al. (2013), who found that all genotypes of Brassica rapa showed notable differences for the ten traits they examined

Table 4: Mean square, range, means, SES, and coefficient of variation for yield and morphological traits

	Mean square			
Traits	**Genotypic variation**	**Range**	**Mean**	**CV%**
Days to 50% Flowering	79.28***	87.0-101	97.66	1.7
100-grain weight	1.38***	1.4-2.41	2.45	11.4
Grain yield (g/plant)	1.85** *	1.33-2.31	2.01	12.2
Panicle length	6.79***	18.1-21.53	19.8	4.6
Plant height	197.34***	56.82-76.3	65.95	4.3
Reproductive tillers	25.95***	11.58-16.32	14.87	10.2
SES Scores	6.64***	3.63-6.88	4.89	20.7
Spikelet sterility	31.11***	15.12-22.06	19.12	10.2

***Significant at $p \leq 0.001$

Table 5 illustrates how the mean performance differed across the several rice genotypes utilized in the experiment. At 101.0 days, Suakoko-10 had the longest days to 50% flowering, whereas FL478 had the shortest (87 days). Days to 50% flowering for the segregating lines were comparable for all genotypes; however, NL F3 and SUF3 flowered before NLF2 and SUF2 (Table 5.3). FL478 had the highest recorded weight (2.61 g) and NERICA-L-19 had the lowest (1.40 g) for the 100-grain weight.

Among the segregating lines, SUF3 had the highest grain weight (2.43 g), while NLF3 had the lowest (2.25 g). NLF3 also recorded the highest grain yield per plant (1.92 g), and SUF2 had the lowest among the segregating lines (1.66 g). Across all genotypes, IR 29 had the lowest grain yield per plant (1.33 g). SUF3 had the longest panicle length (21.03 cm), and FL478 had the shortest (18.1 cm). Plant height ranged from 76.30 cm for NERICA-L-19 to 56.82 cm for FL478, with NLF3 being the shortest among the segregating lines (59.95 cm).

SUF3 had the highest number of reproductive tillers (19.92), while IR 29 had the lowest (11.58). Suakoko-10 showed the highest percentage of sterile

ISSN: 3049-2289

spikelets (22.95%), and NLF2 had the lowest (13.76%). NLF3 recorded the lowest salinity injury score (3.63), indicating strong tolerance, whereas SUAKOKO-10 was most susceptible with a score of 6.88. Overall, NLF3 and SUF3 were the most consistently performing genotypes for most traits. SES scores differed significantly among all rice genotypes.

Table 5: Mean performance of rice genotypes under saline condition

Genotypes	Days to 50% Flowering	100-grain weight(g)	Grain yield (g/plant)	Panicle length (cm)	Plant height (cm)	Reproductive tillers (No. of tillers)	SES Scores	Spikelet sterility (%)
NLF2 (NERICA-L-19 X FL 478)	97.2	2.33	1.75	19.42	75.24	15.41	4.76	13.76
NLF3 (NERICA-L-19 X FL478)	96.7	2.25	1.92	18.31	59.95	16.25	3.63	13.79
SUF2 (SUAKOKO-10 X FL 478)	97.2	2.31	1.66	20.4	67.51	19.78	4.45	18.93
SUF3 (SUAKOKO-10 X FL 478)	96.8	2.43	1.84	21.03	64.33	19.92	4.18	17.49
NERICA-L-19 (Recurrent)	98.5	1.4	1.63	20.45	76.3	13.95	5.91	21.72
SUAKOKO-10 (Recurrent)	101	1.42	1.42	20.13	66.79	12.35	6.88	22.95
FL 478 (Donor)	87	2.61	1.84	18.1	56.82	15.54	3.77	15.12
IR 29 (Susceptible check)	100.3	1.59	1.33	19.06	60.7	11.58	6.38	22.06
S.E	1.7	0.23	0.21	0.91	2.87	1.63	1.04	2.4
CV %	1.7	11.4	12.2	4.6	4.2	11.3	20.6	11.3

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6 Correlation Coefficients of Grain Yield and Yield Components

Table 6 displays the correlation coefficients between rice genotypes' yield and agrophysiological characteristics. Grain yield had a positive and highly significant correlation with 100-grain weight ($r=0.58$; $p<0.01$) and a positive significant correlation with the number of reproductive tillers ($r=0.38$; $p<0.05$), according to correlation coefficients obtained for yield and its components. According to these findings, the main factors influencing yield were the number of reproductive tillers and the 100-grain weight. This outcome is comparable to the findings of Hassan et al. (2016) for 1000-grain weight and Fiyaz et al. (2011) and Babu et al. (2012) for reproductive tillers.

Grain yield per plant showed a significant negative correlation with salinity injury scores and spikelet sterility, while the correlation between days to 50% flowering and grain yield per plant was negatively non-significant. Spikelet sterility exhibited a highly significant negative correlation with grain weight, grain yield, and the number of reproductive tillers, but a positive correlation with both panicle length and salinity injury scores. This finding aligns with the observations made by Hassan et al. (2016) regarding 100-grain weight and grain yield per plant, but differs for the other traits; this discrepancy may be attributed to the different genotypes studied and environmental factors. Plant height demonstrated a non-significant positive correlation with spikelet sterility. Furthermore, plant height showed a significant positive correlation with panicle length, suggesting that an increase in plant height may lead to a corresponding increase in panicle length.

Table 6: Correlation coefficients of yield and agro-physiological traits of four rice generations

	Days to Flowering (days)	Grain weight (g)	Grain yield (g/plant)	Panicle length (cm)	Plant height (cm)	No. of Reprod. Tillers	SES scores	Spikelet sterility (%)
Days to Flowering (days)								
Grain weight(g)	-0.52**							
Grain yield (g/plant)	-0.33ns	0.58***						
Panicle length (cm)	0.37*	-0.07	0.02					
Plant height (cm)	0.29ns	-0.29	-0.01	0.36*				
No. of Reprod. Tillers	-0.12ns	0.54**	0.38*	0.26	-0.22			
SES scores	0.42**	-0.65***	-0.42*	0.11	-0.02	-0.60***		
Spikelet sterility (%)	0.65***	-0.73***	-0.47**	0.19	0.28	-0.43*	0.68***	
Number of tillers	0.17ns	0	0.01	0.23	-0.08	0.65***	-0.19	-0.11

Note: *, ** and *** are the levels of significance at $P<0.05$, $P<0.01$ and $P<0.001$ respectively

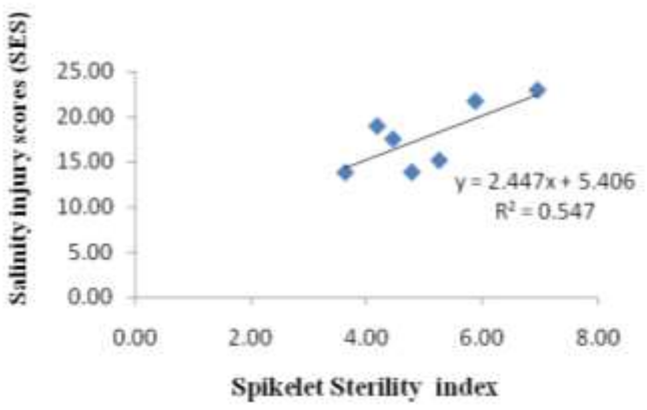

Figure 1: **Relationship of salinity injury scores and spikelet sterility index of seven rice genotypes**

7 Conclusion

The findings of this research suggest that there was sufficient genetic diversity among the materials examined. The NLF3 and SUF3 populations exhibited the strongest performance for all traits analyzed in comparison to NF2, SUF2, and the parental lines. Notably, both high heritability and significant genetic advancement were noted for days to 50% flowering and plant height, whereas the grain yield of the genotypes showed a positive correlation with grain weight and the count of productive tillers. The NF3 populations had the lowest SES value, with the SUF3 population following closely, indicating a better tolerance to salinity.

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Healing Power of Tulsi: How Its Natural Chemicals Protect Human Health

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Tulsi (*Ocimum sanctum*), a member of the Lamiaceae family, is among the most ancient aromatic medicinal herbs, commonly referred to as holy basil. Every part of the plant—including leaves, stems, seeds, roots, and flowers—possesses therapeutic properties, which is why it is often called the "Queen of Herbs." The leaves and flowers are rich in essential nutrients such as fatty acids, β-carotene, calcium, vitamin C, and various volatile compounds that contribute to overall health. Eugenol is the principal bioactive compound found in tulsi, widely utilized in perfumery, flavoring industries, essential oils, and as a local anesthetic and antiseptic in medicine. Additionally, tulsi contains important phytochemicals like alkaloids, glycosides, saponins, and triterpenoids derived from different plant parts.

Due to its wide range of pharmacological activities, tulsi is commonly recommended by practitioners for the management of various ailments, including cough, sore throat, kidney stones, eye disorders, and respiratory diseases. It also exhibits multiple therapeutic properties such as analgesic, anticancer, antiasthmatic, antiemetic, antidiabetic, antifertility, antilipidemic, and hypotensive effects. Furthermore, tulsi demonstrates anti-ulcer, antioxidant, anti-inflammatory, anti-arthritic, antistress, immunomodulatory, and neuroprotective activities.

Introduction

Tulsi (*Ocimum sanctum*), known as holy basil in English and Tulasi in Sanskrit, is a highly valued aromatic herb belonging to the Lamiaceae family. It is also referred to by various regional names such as Manjari, Krishna Tulsi, Trittavu, Tulshi, and Thulsi. The plant is highly branched, covered with fine hairs, and typically grows to a height of 75–90 cm. Its leaves are round to oval-shaped, measuring up to 5 cm in length, while the flowers are purple to cream-colored and produce yellow to reddish flat seeds. Varieties of tulsi include Shri Tulsi (green leaves) and Krishna Tulsi (reddish leaves). The leaves are especially rich in essential oils (Kumar et al., 2010).

Tulsi has long been regarded as a "legendary" and "incomparable" herb with extensive therapeutic and restorative uses, widely distributed throughout India (Jeba et al., 2011). Historical records suggest its use dates back to 4000–5000 B.C. (Monga et al., 2011), with references found in ancient texts such as the Rigveda (Sirkar, 1989). Even today, approximately 80% of the rural population in developing countries relies on traditional herbal medicine systems, as reported by WHO, encouraging ongoing scientific research into medicinal plants (Summy and Patyal, 2016).

Tulsi is nutritionally rich, containing proteins, carbohydrates, fats, calcium, carotene, chromium, copper, iron, nickel, phosphorus, vitamin C, and zinc (Sah et al., 2018). Regular consumption of tulsi leaves and its preparations is believed to prevent diseases, enhance longevity, and improve both physical and mental well-being. It is traditionally used to treat numerous conditions, including anxiety, fever, cough, dysentery, asthma, arthritis, eye disorders, back pain, skin diseases, gastric issues, vomiting, heart diseases, genitourinary disorders, hiccups, infections, malaria, ear pain, common cold, indigestion, constipation, headache, respiratory problems, and diabetes (Bast et al., 2014; Mohan, 2011; Mondal, 2011).

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Extensive scientific studies, including both animal and human experiments, have validated the diverse medicinal properties of tulsi. These include anti-inflammatory, antipyretic, antiallergic, antiasthmatic, antitussive, antiulcer, antiemetic, antispasmodic, antioxidant, antistress, hepatoprotective, cardioprotective, neuroprotective, antihypercholesterolemic, antidiabetic, anticoagulant, adaptogenic, antithyroid, anticataract, anticancer, radioprotective, antihypertensive, analgesic, immunomodulatory, CNS depressant, memory-enhancing, antimicrobial (antiviral, antibacterial, antifungal, antiprotozoal, antimalarial, antihelminthic), antiarthritic, antitoxic, and wound-healing properties (Shukla et al., 2012; Wangcharoen and Morasuk, 2007; Panda and Naik, 2009; Shivananjappa and Joshi, 2012; Manikandan, 2007; Rahman et al., 2011).

Herbal medicine, as an essential component of both traditional and modern healthcare systems, continues to play a significant role in maintaining human health. A large proportion of the global population, especially in developing regions, still depends on plant-based remedies to meet healthcare needs (Cohen, 2014).

Fig: Tulsi Plant

Medicinal properties:

Antispasmodic, appetizer, carminative, galactagogue, stomachic. Basil is antispasmodic, appetizer, carminative, galactagogue, and stomachic. It is used for stomach cramps, gastric catarrh, vomiting, intestinal catarrh, constipation, and enteritis. It had been sometimes used for whooping cough as an antispasmodic.

1. Tulsi has antioxidant properties and reduces blood glucose levels. Thus it is useful for diabetics.
2. Tulsi reduces total cholesterol levels. Thus it is useful for heart disease patients..
3. Tulsi reduces blood pressure.
4. Tulsi is also used to prepare herbal tea. It helps in building up stamina.
5. It has been used for gastric disorders, cough, common colds, malaria, and headaches.
6. It is used as mouth wash for reducing tooth ache
7. Tulsi oil shows larvicidal activity against malarial larva.
8. It has immuno-modulatory properties.
9. It contains phyto-chemicals which provide all these beneficial effects.
10. Many herbal cosmetics contain tulsi. It is also used in skin ointments due to its anti-bacterial properties. Oil extracted from Karpoora Tulsi is used in these preparations.
11. Tulsi acts as insect repellant. So it is used to store grains.
12. Recent research shows that tulsi does have analgesic (pain killer) properties similar to COX 2 inhibitor drugs.
13. Ursolic acid, a chemical in tulsi may have a role as antifertility (contraceptive) agent in future.
14. It has antiviral, antibacterial, ant tubercular, antifungal, antimalarial properties.

Table 1: Major and minor biochemical ingredients found in Tulsi plant with their biological activity

S. No.	Tulsi Species	Biochemical Component(s)	Characteristics	Biological Activity
1.	*Ocimum sanctum* (Krishna Tulsi)	Eugenol	Volatile aromatic compound (phenolic)	Antimicrobial, anti-inflammatory, antioxidant, analgesic
2.	*Ocimum sanctum* (Rama Tulsi)	Ursolic acid	Pentacyclic triterpenoid	Anticancer, anti-ulcer, hepatoprotective, anti-diabetic
3.	*Ocimum tenuiflorum*	Linalool	Terpenoid alcohol, fragrant oil	Antimicrobial, stress-relieving, sedative
4.	*Ocimum gratissimum*	Caryophyllene	Sesquiterpene compound	Anti-inflammatory, insecticidal, analgesic
5.	*Ocimum basilicum*	Rosmarinic acid	Phenolic antioxidant	Antiviral, anti-allergic, anti-inflammatory
6.	*Ocimum sanctum*	Apigenin	Flavonoid pigment	Antioxidant, anti-cancer, cardio-protective
7.	*Ocimum tenuiflorum*	β-Sitosterol	Plant sterol	Anti-cholesterol, immune-modulatory, anti-diabetic
8.	*Ocimum sanctum*	Oleanolic acid	Triterpenoid compound	Anti-inflammatory, hepatoprotective, antioxidant
9.	*Ocimum gratissimum*	Chavicol	Phenolic aromatic compound	Antibacterial, antiseptic, antioxidant
10.	*Ocimum sanctum*	Tannins, Saponins	Polyphenolic compounds and glycosides	Antioxidant, adaptogenic, antimicrobial, immune-boosting

Health benefits of tulsi in our daily life:

1. **Healing Power:** The tulsi plant has many medicinal properties. The leaves are a nerve tonic and also sharpen memory. They promote the removal of the catarrhal matter and phlegm from the bronchial tube. The leaves strengthen the stomach and induce copious perspiration. The seed of the plant are mucilaginous.
2. **Fever and Common Cold:** Eugenol, a chemical compound that found in tulsi (*Ocimum sanctum*), may help to reduce fever Fever and Common Cold.The leaves of basil are specific for many fevers. During the rainy season, when malaria and dengue fever are widely prevalent, tender leaves, boiled with tea, act as preventive against these diseases. In case of acute fevers, a decoction of the leaves boiled with powdered cardamom in half a liter of water and mixed with sugar and milk brings down the temperature. The juice of tulsi leaves can be used to bring down fever. Extract of tulsi leaves in fresh water should be given every 2 to 3 hours. In between one can keep giving sips of cold water. In children, it is every effective in bringing down the temperature.
3. **Coughs:** Eugenol, a chemical compound that found in tulsi (*Ocimum sanctum*), may help to reduce cough. Tulsi is an important constituent of many Ayurvedic cough syrups and expectorants. It helps to mobilize mucus in bronchitis and asthma. Chewing tulsi leaves relieves cold and flu.
4. **Sore Throat:** Tulsi has contain antimicrobial properties that help fight against infections that cause sore throat. Water boiled with basil leaves can be taken as drink in case of sore throat. This water can also be used as a gargle.
5. **Respiratory Disorder:** Due to the presence of compounds like camphene, eugenol, and cineole, tulsi cures viral, bacterial, and fungal infections of the respiratory system. These are chemical compounds present in tulsi plant. Thse are responsible for the control the disorders like bronchitis & tuberculosis. The herb is useful in the treatment of respiratory system disorder. A decoction of the leaves, with honey and ginger is an effective remedy for bronchitis, asthma, influenza, cough and cold. A decoction of the leaves, cloves and common salt also gives immediate relief in case of influenza. They should be boiled in half a liter of water till only half the water is left and add then taken.
6. **Kidney Stone:** Tulsi contains several chemical compounds such as eugenol, caryophyllene, and methyl eugenol. These chemical compounds are responsible for the help to prevent the kidney stones.Basil has strengthening effect on the kidney. In case of renal stone the juice of basil leaves and honey, if taken regularly for 6 months it will expel them via the urinary tract.
7. **Heart Disorder:** Tulsi has been traditionally used to treat cardiovascular diseases and manage general cardiac health because they are contains several chemical compounds that may help to prevent the heart disease such as Eugenol and Ursolic acid.These chemical compounds are responsible for the help to prevent the Heart Disorder. Eugenolan antioxidant that helps lower cholesterol levels and blood pressure, and protects the heart from free radicals and Ursolic Lowers cortisol levels, which can help reduce stress and stress-related heart disease.
8. **Children's Ailments:** Common pediatric problems like cough cold, fever, diarrhea and vomiting respond favorably to the juice of basil leaves. If pustules of chicken pox delay their appearance, basil leaves taken with saffron will hasten them.
9. **Stress:** Tulsi contains antioxidants that can help to reduce the oxidative stress, which is linked to chronic diseases. Basil leaves are regarded as an 'adaptogen' or anti-stress agent. Recent studies have shown that the leaves afford significant protection against stress. Even healthy persons

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can chew 12 leaves of basil, twice a day, to prevent stress. It purifies blood and helps prevent several common elements.

10. **Mouth Infections:** Preclinical studies have also shown that Tulsi contain some phytochemicals coumpounds such as eugenol, rosmarinic acid, apigenin, myretenal, luteolin, β-sitosterol, and carnosic acid prevented chemical-induced skin, liver, oral, and lung cancers. These chemical compounds helps to control the mouth infection. The leaves are quite effective for the ulcer and infections in the mouth. A few leaves chewed will cure these conditions.

11. **Skin Disorders:** Preclinical studies have also shown that Tulsi contain some phytochemicals coumpounds such as eugenol, rosmarinic acid, apigenin, myretenal, luteolin, β-sitosterol, and carnosic acid prevented chemical-induced skin, liver, oral, and lung cancers. These chemical compounds helps to control the skin diseases. Applied locally, basil juice is beneficial in the treatment of ringworm and other skin diseases. It has also been tried successfully by some naturopaths in the treatment of leucoderma.

12. **Teeth Disorder:** The herb is useful in teeth disorders. Its leaves, dried in the sun and powdered, can be used for brushing teeth. It can also be mixed with mustered oil to make a paste and used as toothpaste. This is very good for maintaining dental health, counteracting bad breath and for massaging the gums. It is also useful in pyorrhea and other teeth disorders.

13. **Headaches:** Tulsi Is A Natural Headache Reliever Which Can Also Relieve Migraine Pain. Basil makes a good medicine for headache. A decoction of the leaves can be given for this disorder. Pounded leaves mixed with sandalwood paste can also be applied on the forehead for getting relief from heat, headache, and for providing coolness in general.

14. **Eye Disorders:** Tulsi's Anti-Inflammatory Properties Help Promote Eye Health By Preventing Viral, Bacterial And Fungal Infections. It Also Soothes Eye Inflammation and Reduces Stress. Basil juice is an effective remedy for sore eyes and night-blindness, which is generally caused by deficiency of vitamin A. Two drops of black basil juice are put into the eyes daily at bedtime.

Conclusion:

It is observed from various scientific studies that Tulsi protects from many modern and traditional health related disorders like radiation, stress, cancers, diabetes, aging, various infections not only in mankind but also in animals and plants. It enhances the immune system to adopt in any environment. All these medicinal ingredients makes tulsi a must have for longer and peaceful life. This small plant is certainly a very good source of medicinal properties. It has many vital properties such as anti-stress, anti-cancers, anti-oxidants, anti-inflammatory, anti-microbial, anti-radiation, insecticidal, insect repellent, flavoring, coloring and many other uncountable properties. They are largely used in ayurvedic medicines. It has not only medicinal properties but also nutritional, spiritual properties which are only present in this plant; thus, it is regarded as “Queen of Green Medicines.”

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Application of Biotechnology in Aquaculture: Current Status, Advances, and Future Prospects

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Aquaculture is one of the fastest-growing food production sectors globally, and biotechnology has emerged as a transformative force in advancing its productivity, sustainability, and disease management. This review examines key applications of biotechnology in aquaculture, including genetic improvement through selective breeding and marker-assisted selection (MAS), chromosome engineering, transgenesis, reproductive biotechnology, disease diagnostics and vaccine development, probiotics, metagenomics, nutrigenomics, cryopreservation, post-harvest preservation, and marine natural products. Landmark achievements such as the AquAdvantage salmon, surrogate broodstock technology, and next-generation sequencing (NGS)-enabled genomic tools are discussed in the context of advancing sustainable aquaculture.

Introduction

Global fish demand continues to rise, while natural fisheries are harvested at or beyond sustainable limits, making aquaculture the primary means of meeting this demand (Lakra and Ayyappan, 2003). Aquaculture now contributes significantly to global food security and national GDPs, particularly across Asia. India alone has developed a multi-billion-dollar aquaculture sector driven substantially by biotechnological innovations (Shinde and Sukhdhane, 2023). The success of aquaculture depends on four critical pillars: seed quality, feed optimization, disease management, and environmental sustainability, all of which have been profoundly advanced by modern biotechnology. This review synthesizes current knowledge on the major biotechnological applications in aquaculture, highlighting achievements, limitations, and future directions.

Genetic Improvement: Selective Breeding and Molecular Markers

Selective breeding has delivered major productivity gains in aquaculture. Genetically Improved Farmed Tilapia (GIFT), Jayanti Rohu, improved common carp, and Atlantic salmon are landmark examples. The Central Institute of Freshwater Aquaculture (CIFA) in India introduced Jayanti Rohu in 1997 with approximately 17% higher growth rates than unimproved stock, and subsequently developed disease-resistant strains resistant to Aeromonas hydrophila (Mahapatra et al., 2017). Selective breeding for Specific Pathogen Resistant (SPR) shrimp and fish strains is actively pursued worldwide to achieve disease-free aquaculture.

Marker-Assisted Selection (MAS) has become integral to modern breeding programs, enabling selection for traits not visible externally, such as disease resistance and carcass composition. Molecular markers, including SNPs, SSRs, AFLP, VNTR, RFLP, and RAPD, allow identification of quantitative trait loci (QTLs) associated with economically important traits. The emergence of Next Generation Sequencing (NGS) has dramatically reduced the cost and accelerated the identification of genome-wide SNP markers, making genomic selection increasingly feasible (Shinde and Sukhdhane, 2023). PCR-based hybrid identification kits, such as the kit developed by CIFA to distinguish Labeo rohita, Catla catla, and their hybrids, have also improved seed quality assurance in hatcheries.

Chromosome Engineering and Sex Control

Chromosome engineering encompasses triploidy induction, tetraploidy, gynogenesis, and androgenesis, and has been applied extensively in cultured fish to achieve sterility, sex control, and hybrid improvement (Lakra and Ayyappan, 2003). Triploid fish, carrying three chromosome sets, are functionally sterile due to failure of homologous chromosome pairing during meiosis, which is highly desirable in salmonid aquaculture to prevent farmed fish from interbreeding with wild populations. Triploidy is induced by exposing fertilized eggs to temperature shock, hydrostatic pressure, or chemicals such as cytochalasin-B. Tetraploid broodstock are used to mass-produce sterile triploids through interploidy crosses with diploids

Gynogenesis produces embryos with exclusively maternal inheritance, enabling all-female populations and rapid inbreeding within one generation. Androgenesis, development from paternal genetic material only, can generate all-male populations and is valuable for recovering genotypes from cryopreserved sperm. Hormonal sex reversal using sex steroids during early development is documented for over 44 species of gonochoristic and hermaphroditic fish, providing a practical route to monosex culture where one sex is commercially preferred (Lakra and Ayyappan, 2003).

Transgenic Fish and Genetically Modified Organisms

Transgenesis is the stable introduction of exogenous DNA into a host genome, offering powerful opportunities to modify traits in commercially important aquaculture species. Since the first transgenic fish was produced in China in 1985, the technology has been applied to numerous species, with the most dramatic results in salmonids, where growth enhancements of 3–30 times that of non-transgenic controls have been reported (Lakra and Ayyappan, 2003). AquAdvantage salmon, developed by AquaBounty Technologies, carries a Chinook salmon growth hormone gene under the control of an ocean pout antifreeze protein promoter, enabling year-round growth and market-size attainment in 16–18 months rather than three years (Shinde and Sukhdhane, 2023). GloFish, a transgenic zebrafish expressing fluorescent proteins, is commercially available for the ornamental fish trade.

Research in fish transgenics has also targeted cold tolerance through introduction of antifreeze protein (AFP) genes from winter flounder into Atlantic salmon and goldfish, improving survival at temperatures lethal to controls (Lakra and Ayyappan, 2003). Embryonic stem cell (ESC) technology represents the most promising future platform for transgenic fish production, allowing precise in vitro gene manipulation and stable germ-line integration. Scientific prerequisites for commercial success include efficient mass gene transfer, suitable promoters, identified target genes, and thorough safety and environmental risk assessments.

Reproductive Biotechnology and Induced Breeding

Modern reproductive biotechnology has transformed hatchery management. Gonadotropin Releasing Hormone (GnRH), the central regulator of vertebrate reproduction, is now the most effective tool for induced breeding. Recombinant DNA technology and protein engineering have produced synthetic super-active GnRH analogues including Ovaprim, Ovatide, and Ovapel that induce spawning at lower doses through enhanced receptor binding affinity achieved by amino acid modifications at position 6 (Shinde and Sukhdhane, 2023). Kisspeptin, a newly characterized neuropeptide, has also been demonstrated to enhance reproductive performance in fish. Fluorescent Activated Cell Sorting (FACS) enables separation of viable, motile spermatozoa from dead cells in hatchery milt, improving fertilization success.

Surrogate broodstock technology represents a paradigm shift in reproductive biotechnology.

Primordial germ cells (PGCs) from a donor species are transplanted into the embryo of a closely related, more easily cultured recipient species, which then produces the donor's gametes after maturation. The "tuna from mackerel" model illustrates how this approach can enable hatchery production of large, difficult-to-breed species while saving time, space, and cost (Yoshizaki and Yazawa, 2019). This technology holds equal promise for conservation of endangered aquatic species.

Disease Diagnosis, Vaccines, and Health Management

Disease costs the aquaculture industry over USD 6 billion annually (Leung and Bates, 2013). Biotechnology has transformed management at the stages of diagnosis, prophylaxis, and therapy. PCR technology enables pathogen detection at single-copy sensitivity, far exceeding conventional culture-based methods. PCR-based diagnostics are now available for virtually all OIE-listed aquatic pathogens and are routine in the certification of Specific Pathogen Free (SPF) seed (Shinde and Sukhdhane, 2023). Next-generation vaccines for finfish include protein subunit vaccines, genetically engineered organisms, and DNA vaccines. Canada has approved the world's first commercial DNA vaccine against infectious hematopoietic necrosis virus (IHNV) in salmon. RNA interference (RNAi) technology has demonstrated experimental pathogen protection, though commercial application remains forthcoming.

Probiotics act as both gut supplements and water-quality management agents, and are increasingly used to reduce pathogen load, maintain healthy gut microbiota, and convert harmful nitrogenous compounds to benign forms. Their role as sustainable alternatives to antibiotics is particularly significant given rising global concerns about antimicrobial resistance (AMR) in aquaculture systems (Lakra and Ayyappan, 2003). Immunostimulants such as glucans, chitins, and levamisole enhance innate immune responses in fish, while microbial products including lipopolysaccharides and peptidoglycans stimulate shrimp immunity.

Post-Harvest Biotechnology: Natural Preservatives for Seafood Quality

Biotechnology also contributes to post-harvest quality management of aquaculture products. Nisin, a bacteriocin produced by Lactococcus lactis, is the most widely studied natural antimicrobial in seafood preservation and holds GRAS (Generally Recognized as Safe) status approved by the FDA and the European Union (Ucar et al., 2020). Ucar et al. (2020) investigated nisin at 0.2%, 0.4%, and 0.8% (w/v) on sea bass (Dicentrarchus labrax) fillets stored at 4 ± 2 °C. Shelf life was extended by two days in nisin-treated groups (8 days) compared to untreated controls (6 days). Nisin-treated fillets showed significantly lower biochemical spoilage indicators peroxide value, TBARS, free fatty acids, TVB-N, and pH as well as lower total mesophilic, psychrotrophic, and Enterobacteriaceae counts. Sensory evaluation confirmed superior acceptability of treated fillets throughout storage, with no adverse effect on cooked flavour or aroma. These findings demonstrate that bacteriocin-based preservation is a viable, biotechnology-derived strategy for extending the freshness of aquaculture products in line with consumer preferences for natural additives.

Metagenomics and Nutrigenomics

Metagenomics enables comprehensive characterization of microbial communities in aquaculture systems without the need for cultivation. By analyzing the total genetic content of samples, metagenomics identifies candidate probiotic organisms from the microbiomes of healthy animals, screens for AMR genes using shotgun approaches, bioprospects for novel bioactive proteins in marine ecosystems, and profiles the microbial composition of biofloc and pond sediments (Shinde and Sukhdhane, 2023). Amplicon metagenomics targeting conserved marker genes such as 16S rRNA enables high-resolution diversity analysis and can serve as a surveillance platform for simultaneously detecting all pathogens in an aquaculture system.

Nutrigenomics is the study of interactions between dietary nutrients and gene expression. It is essential for evaluating the consequences of replacing fishmeal with plant proteins, poultry by-products, or other alternative ingredients. Understanding how dietary changes alter metabolic and biochemical pathways at the molecular level supports the rational design of species-specific feeds that optimize growth, immunity, and welfare. Advances in quantitative PCR, Droplet Digital PCR (ddPCR), and NGS have greatly strengthened nutrigenomic research, and this field is set to play an increasingly important role in sustainable, cost-effective aquaculture feed development (Shinde and Sukhdhane, 2023).

Cryopreservation, Gene Banking, and Marine Natural Products

Cryopreservation at -196 °C in liquid nitrogen enables long-term storage of fish sperm (milt), which has been achieved for virtually all commercially important cultured species (Lakra and Ayyappan, 2003). Aquatic gene banks built on cryopreserved gametes provide a genetic resource base for future breeding programs analogous to plant gene banks that have underpinned crop improvement for decades. A major limitation is that viable cryopreservation protocols exist only for male gametes in finfish; promising advances in shrimp embryo cryopreservation may expand this capability to crustaceans.

Marine organisms represent a vast, underexplored source of biologically active natural products, including pharmaceutical compounds, pigments, sterols, alginates, enzymes, and immunostimulants. Novel compounds from horseshoe crab blood extracts have demonstrated anticancer activity, and marine seaweeds provide unique bioactive compounds with medicinal properties. Microbial biotechnology for aquaculture, encompassing biofertilization, biofiltration, probiotic applications, and microbial enzyme supplementation in feeds, further enhances productivity and environmental sustainability (Lakra and Ayyappan, 2003).

Conclusions and Future Perspectives

Biotechnology has fundamentally reshaped aquaculture over the past four decades, with practical applications spanning genetic improvement, reproduction, disease management, feed science, post-harvest technology, and genetic resource conservation. Key achievements are the commercialization of AquAdvantage salmon, NGS-enabled genomic selection, PCR diagnostics, DNA vaccines, and natural bacteriocin-based preservatives, which demonstrate the breadth and depth of biotechnology's impact on the sector.

Future priorities include genomic selection using whole-genome sequencing, CRISPR-Cas9-based precision trait editing, expansion of surrogate broodstock technology to a wider range of species, and integration of metagenomic and nutrigenomic data into real-time farm management systems. Realizing these opportunities requires sustained research investment, evidence-based regulatory frameworks, and societal dialogue on the acceptance of biotechnologically modified aquaculture products. Biotechnology will remain indispensable to ensuring that global aquaculture expansion is productive, sustainable, and capable of contributing to food security for future generations.

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Permaculture Farming: A Sustainable Approach to Agriculture

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Permaculture farming is a sustainable and ecologically based agricultural system that works in harmony with nature to create self-sufficient and resilient farming ecosystems. Developed by Bill Mollison and David Holmgren in the 1970s, permaculture emphasizes principles such as earth care, people care, and fair share. It integrates diverse farming components including crops, trees, livestock, and water resources to improve soil fertility, conserve water, enhance biodiversity, and reduce dependence on chemical inputs. Key practices include mixed cropping, agroforestry, composting, rainwater harvesting, and livestock integration. Permaculture provides environmental, economic, and social benefits by promoting resource conservation, lowering production costs, diversifying farm income, and strengthening food security. Although it requires technical knowledge, careful planning, and long-term commitment, it offers a sustainable solution to challenges such as soil degradation, climate change, and livelihood insecurity. In the Indian context, permaculture aligns well with traditional farming systems and has significant potential for improving the resilience and sustainability of smallholder agriculture.

Introduction

Permaculture farming is an ecologically based agricultural system that aims to create sustainable and self-sufficient farming ecosystems by working in harmony with nature. The concept was introduced in the 1970s by Bill Mollison and David Holmgren, who envisioned a form of agriculture that could be maintained indefinitely without degrading natural resources. Over time, permaculture has expanded beyond agriculture to include sustainable living practices, ecological design, and community development. At its core, permaculture is about observing natural systems and replicating their patterns and relationships in agricultural landscapes.

Ethics of Permaculture

1. **Earth Care:** Permaculture emphasizes the protection and regeneration of natural resources such as soil, water, forests, and biodiversity. Farmers adopt practices like organic manuring, mulching, and tree planting to maintain ecological balance. This ensures that the land remains productive for future generations.
2. **People Care:** This principle focuses on meeting human needs such as food, shelter, and livelihood in a sustainable manner. Permaculture systems aim to provide healthy food and improve the quality of life for farmers and communities.
3. **Fair Share (Return of Surplus):** Permaculture promotes responsible use of resources and encourages sharing of surplus produce. It helps in reducing waste and ensuring equitable distribution of resources.

Principles of Permaculture

1. **Observe and Interact:** Farmers carefully study natural conditions such as climate, soil type, rainfall, and biodiversity before designing the farming system. This helps in making better management decisions.
2. **Catch and Store Energy:** Natural resources like sunlight, rainwater, and organic matter are captured and stored efficiently. For example, rainwater harvesting structures are used to store water for future use.

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3. **Produce No Waste:** All farm waste is recycled. Crop residues, kitchen waste, and animal dung are converted into compost or manure, reducing external inputs.
4. **Use Diversity:** Growing a variety of crops and integrating trees and animals increases system stability and reduces risks from pests and diseases.
5. **Integrate Rather Than Segregate:** Different farm components such as crops, livestock, and trees are interconnected so that each supports the other, creating a balanced ecosystem.

Key Practices in Permaculture Farming

1. **Polyculture (Mixed Cropping):** In permaculture, multiple crops are grown together instead of a single crop. This improves soil fertility, reduces pest attacks, and increases productivity. For example, legumes can be grown with cereals to naturally add nitrogen to the soil.
2. **Agroforestry:** Trees are integrated with crops and livestock. They provide shade, prevent soil erosion, and contribute organic matter through leaf litter. Fruit and timber trees also generate additional income.
3. **Soil Management:** Healthy soil is maintained through composting, green manuring, mulching, and vermi-composting. These practices improve soil structure, moisture retention, and microbial activity.
4. **Water Management:** Efficient water use is ensured through rainwater harvesting, farm ponds, contour bunding, and drip irrigation. These methods help conserve water and improve crop productivity.
5. **Livestock Integration:** Animals such as poultry, ducks, goats, and cattle are included in the farming system. They provide manure, help in pest control, and contribute to farm income.

Benefits of Permaculture Farming

Permaculture offers a wide range of environmental, economic, and social benefits that contribute to sustainable agriculture and rural development. Environmentally, it improves soil fertility through the use of organic matter, crop rotation, and natural farming techniques. It also conserves water by promoting rainwater harvesting, mulching, and efficient irrigation practices. In addition, permaculture enhances biodiversity by integrating different crops, trees, animals, and beneficial organisms within the farming system. The reduced dependence on chemical fertilizers and pesticides helps minimize soil and water pollution and protects the ecosystem. Economically, permaculture lowers production costs because farmers rely more on locally available resources and recycled farm inputs. It also provides multiple sources of income through the cultivation of crops, fruits, vegetables, livestock, fish, and other farm products, thereby reducing financial risk and increasing farm resilience. Socially, permaculture strengthens food security by ensuring a stable supply of diverse and nutritious food throughout the year. It encourages community participation, knowledge sharing, and cooperation among farmers. Furthermore, it promotes self-reliance and sustainable livelihoods, helping rural communities become more resilient and independent.

Challenges of Permaculture Farming

Despite its many advantages, permaculture also faces certain challenges and limitations. One major challenge is that permaculture is knowledge intensive, requiring farmers to have proper training and a good understanding of ecological systems, crop interactions, and sustainable farming practices for successful implementation. Establishing a permaculture system also demands significant initial effort, careful planning, and time before the system becomes fully stable and productive. Unlike conventional farming, the economic benefits of permaculture are often realized gradually over the long term, which may discourage farmers who expect

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quick returns from agriculture. In addition, marketing can sometimes become difficult because permaculture farms usually produce a wide variety of products in smaller quantities, making it challenging to find organized markets and buyers for all items. Therefore, while permaculture is highly sustainable, farmers need patience, technical knowledge, and proper market support to achieve long-term success.

Permaculture in Indian Context

Permaculture has strong relevance in the Indian agricultural context, particularly for small and marginal farmers who depend on limited resources and face increasing challenges from climate variability and soil degradation. The principles align closely with traditional Indian farming practices such as mixed cropping, agroforestry, and integration of livestock. In India, diverse agro-climatic conditions—from arid regions to high-rainfall zones like West Bengal, Assam, Meghalaya, and Tripura, offer great potential for adopting permaculture systems that combine crops, trees, water bodies, and animals. Techniques such as rainwater harvesting, composting, mulching, and use of indigenous seeds help reduce dependence on chemical inputs while improving soil fertility and resilience. Permaculture also supports livelihood security by diversifying farm outputs, including fruits, vegetables, fish, and livestock products. As climate change impacts intensify, permaculture provides a sustainable, low-cost, and ecologically sound approach that can enhance productivity, conserve natural resources, and ensure long-term food security in India.

Role in Climate Change Mitigation

Permaculture plays a significant role in mitigating climate change by promoting sustainable land use practices that reduce greenhouse gas emissions and enhance carbon sequestration. The concept emphasizes working with natural ecosystems, which helps restore ecological balance. One of the key contributions of permaculture is improving soil health through practices like composting, mulching, and reduced tillage, which increase soil organic carbon and act as a carbon sink. The integration of trees in farming systems (agroforestry) further enhances carbon sequestration by capturing atmospheric carbon dioxide and storing it in biomass.

Permaculture also reduces dependence on synthetic fertilizers and pesticides, whose production and use contribute significantly to greenhouse gas emissions. By using organic inputs and recycling farm waste, emissions are minimized while maintaining soil fertility. Efficient water management techniques such as rainwater harvesting and contour bunding improve resilience to droughts and floods, which are becoming more frequent due to climate change. Additionally, crop diversity and integrated farming systems increase the adaptability of farms to changing climatic conditions, reducing the risk of crop failure.

Conclusion

Permaculture farming is a holistic and sustainable agricultural approach that combines ecological principles with practical farming techniques. It focuses on long-term productivity, environmental conservation, and social well-being. Although it requires proper knowledge and planning, it offers a promising solution for sustainable agriculture and rural development.

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Nanotechnology: A Sustainable Approach for Nematode Management

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Nematodes are tinny round worms that live in different environment. In agriculture, nematodes usually play the role of pests. Specifically, plant-parasitic nematodes (PPNs) such as root-knot nematodes (*Meloidogyne* spp.), cyst nematodes (*Heterodera* spp.), *Radopholus*, and *Pratylenchus* are among major pests that weaken plants and reduce the harvest. PPNs are thought to cause $100+ billion worth of annual crop losses worldwide. The conventional methods of pest control include chemical nematicides, crop rotation, soil heating, and planting resistant varieties. Nevertheless, they tend to offer only temporary solutions. For instance, even though chemical nematicides are quite efficient, they are highly risky to use because they are toxic and can cause pest resistance development. In view of the fact that environmentally friendly agricultural practices become the major concern in contemporary agriculture, alternative methods of nematode control must be found. In this regard, nanotechnology, which is a science devoted to manipulating materials at the level of molecules and atoms, becomes especially significant.

Nanotechnology:

Principle of Nanotechnology and Applications of Nanoparticles (NPs) in Agriculture Nanotechnology consists of particles sized between 1-100 nm, where their unique physical and chemical characteristics such as large specific surface area, increased reactivity, alterable solubility, and membrane permeability become apparent. Therefore, NPs could be employed in the domain of agriculture as an innovative means to enhance disease diagnosis, delivery of pesticides, pest control, and evaluation of the condition of the soil.

Nano Formulated Nematicides:

Nano-formulations are designed for pesticide delivery purposes. They imply encapsulation, emulsification, and coating of pesticides by NPs. These types of nematicides have a number of advantages compared to regular pesticides, including their slower delivery rates and greater ability to penetrate into tissues of host plants or pests' bodies. Moreover, NP-delivered nematicides require smaller amounts of pesticides because they are highly bioavailable.

Examples:

Fenamiphos loaded with polymeric nanoparticles increased the mortality rate of *Meloidogyne incognita* at a decreased dose. Furthermore, neem oil nanoemulsions were more stable in the field environment and had higher nematicidal activity than raw neem extracts.

Metal and Metal Oxide Nanoparticles:

The tiny Metal and Metal Oxide Nanoparticles made from Metal elements like Ag, ZnO, CuO and Fe_3O_4 are really good at killing nematodes. This is because Metal and Metal Oxide Nanoparticles have an ability to make something called ROS molecules.

Metal and Metal Oxide Nanoparticles can break the layer of nematodes, which is, like a protective wall. They can also mess with the way nematodes make energy how their enzymes work. Even affect their nervous system. This can cause the nematodes to become paralyzed and eventually die from the Metal and Metal Oxide Nanoparticles.

Notable Studies:

For instance, AgNPs obtained by a biological method from plant extracts (Azadirachta indica and Allium sativum) caused over 90% mortality rate in juvenile M. incognita. Also, addition of ZnO NPs to the soil suppressed gall development and nematode population density.

Green/Biogenic Nanoparticles:

As mentioned above, nanoparticles could be synthesized from biological sources (plants, microorganisms, etc.). Thus, they are highly biodegradable and not harmful for non-target organisms.

Advantages:

- incorporation of biological nematicidal substances into nanoparticles (azadirachtin, allicin);
- low toxicity;
- compatibility with organic agricultural practice.

Example,

AgNPs mediated by neem extract demonstrated substantial inhibition of hatching process and restricted movement of *Heterodera cajani* juveniles.

Nanocarriers for Biocontrol Agents:

Nanocarriers are able to encapsulate microbial and fungal agents and slowly deliver them to target places. Nanocarriers ensure higher survivability of bioagents in soil, improve colonization efficiency by binding them to plant roots, and help to target them to nematodes' eggs or juveniles.

Applications:

- Pasteuria penetrans (a bacterial parasite of nematodes) could be delivered to the soil using nanocarriers, thus increasing its shelf life and uniformity;
- fungal biocontrol agents (Pochonia chlamydosporia and Purpureocillium lilacinum) have also been successfully carried in nanoparticles to increase egg parasitism efficacy.

Nano-sensors for Detection of Nematodes:

Rapid and reliable detection of nematodes is critical for effective pest control. Hence, biosensors using carbon nanotubes, quantum dots, and gold nanoparticles may prove useful in:

- Finding out whether there is DNA and protein of nematode in soil and root samples
- Identifying whether there is any change in soil quality and behavior of nematode
- Controlling nematodes is a deal and we can do it with precision agriculture practices.

Interactions of Nanoparticles Nematode:

- There are many reasons why nanoparticles affect nematodes, including
- The physical harm that happens when nanoparticles touch the nematodes and hurt them;
- internal penetration;
- Disruption of respiration, reproduction, and neuromuscular processes in nematodes;
- Generation of oxidative stress via ROS production affecting lipids, proteins, and nucleic acids.

Advantages of Using Nanotechnology for Nematode Control:

- Environmentally friendly method;
- Economical because it requires fewer inputs;
- targeting abilities;
- effectiveness for managing nematocidal resistant species.

Limitations and Challenges:

However, there are still certain limitations that should be addressed:

- ecological safety as long-term influence of NPs on the soil health, pollinators, and water ecosystems is still unknown;
- lack of regulations related to the production, distribution, and use of nano agrochemicals;
- high costs of manufacturing processes and insufficient large-scale scalability of green synthesis techniques;
- limited number of experiments conducted in the field;
- farmers' low awareness regarding proper usage and disposal of nano agrochemicals.

Future Directions:

There are some things we need to think about in the field of nanotechnology. We could make nanoparticles that kill nematodes or act as fertilizer or help us diagnose problems.

We should also think about making systems that deliver medicine and have sensors and things that carry particles.

Using things made from both biology and nanotechnology could be really good because they can work together to make something even better.

We need to have rules for nanotechnology so that we can use nanotechnology properly. Companies and public organizations have to work to make sure nanotechnology is good for agriculture.

Nanotechnology is very important. We need to use nanotechnology in a good way to help us grow food and take care of the earth.

Conclusion:

Nanotechnology is really helping us with nematodes in a way that's good, for the environment. Nanotechnology can kill nematodes. It can make the things that fight nematodes work even better. We can use Nanotechnology to keep an eye on what the nematodesre doing. We can also use Nanotechnology to see how healthy the soil is. Nanotechnology is a help when it comes to dealing with nematodes.

We have to be careful when we use nanotechnology and nanoparticles. We need to make sure that these methods are good for the environment and do not cost money. We also need to make sure that everyone can use nanotechnology and nanoparticles.

Nanotechnology and nanoparticles are very important, for this. So we need to use nanotechnology and nanoparticles in the way.

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Hydroponics for Bell Peppers (Capsicum annum) and Specialty Crops: Opportunities and Practices

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Hydroponics has emerged as an efficient cultivation method for peppers and premium specialty crops by enabling precise control over water, nutrients, and root-zone conditions. This soilless production system supports higher yield potential, improved fruit quality, and more uniform crop development while reducing dependence on soil and minimizing issues related to soil-borne diseases. For peppers, hydroponic systems such as drip irrigation with inert substrates are particularly suitable because they allow effective nutrient management during the crop's long fruiting period. Premium specialty crops, including high-value herbs, leafy greens, and exotic vegetables, also benefit from hydroponics due to the ability to produce clean, marketable, and year-round harvests in controlled environments. The major opportunities of hydroponics lie in water use efficiency, space optimization, protected cultivation, and supply of quality produce to premium markets. However, successful adoption requires proper system selection, careful fertigation, continuous monitoring of pH and EC, and crop-specific management practices. Overall, hydroponics represents a sustainable and profitable pathway for advancing pepper and specialty crop production in modern horticulture.

Introduction

The global food system is increasingly under pressure from rapid urbanization, diminishing arable land, water scarcity, and the mounting challenges posed by climate change, all of which have intensified interest in innovative, resource-efficient agricultural technologies. Hydroponics a soilless cultivation technique that delivers balanced nutrient solutions directly to plant roots under controlled environmental conditions has emerged as a transformative response to these challenges. Hydroponics is widely used for growing vegetables, high-value crops, and flowers, producing significantly higher yields compared to conventional soil-based agriculture(Pimentel-Pujols et al., 2026). Among its most commercially significant applications is the cultivation of *Capsicum annuum* (peppers), a crop of immense global importance. Global vegetable production exceeded 1.2 billion tons in 2022, with bell pepper alone accounting for 37 million tons, a crop of high value owing to its versatility, commercial demand, and nutritional properties. The adoption of hydroponic systems for pepper production has been further fueled by the expanding market for premium specialty crops, with the global hydroponic vegetables market valued at approximately USD 4.96 billion in 2023, projected to grow to USD 14.16 billion by 2032 at a CAGR of 12.35% (*Hydroponics Market Overview 2026 to 2035*, n.d.). Peppers, alongside tomatoes, cucumbers, and leafy greens, are among the most commonly cultivated hydroponic crops, with specialty crops and ornamental plants gaining increasing attention for premium markets and research applications. The physiological requirements of pepper plants make them particularly well-suited — yet also distinctly demanding as hydroponic candidates. Research has demonstrated that nutrient electrical conductivity (EC) significantly affects the growth and physiological responses of sweet pepper (*Capsicum annuum* L.) in hydroponic culture, where very high or very low EC treatments clearly decrease plant

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height, stem diameter, shoot dry weight, and leaf net photosynthetic rate(Ding et al., 2022). Optimizing such parameters is central to achieving the high yields and fruit quality expected in premium markets. Studies on the effect of different nutrient solutions on hydroponic *Capsicum* varieties confirm that maintaining appropriate pH and EC — typically around pH 6.0 and EC 2.8 dS·m^{-1} is critical for growth, yield, and quality outcomes. Furthermore, recent advances in controlled environment agriculture (CEA), including IoT-based monitoring, automated fertigation, and precision lighting, have enhanced the scalability and reliability of pepper hydroponics (J. Rahman et al., 2023). The increasing consumer demand for fresh, pesticide-free, and locally sourced produce is inducing growers to shift to hydroponic systems promising year-round cultivation within controlled environments, and the high degree of control over nutrient availability in hydroponic systems leads to substantially higher yields than in soil-based systems. Together, these technological, agronomic, and market dynamics present compelling opportunities for producers, researchers, and policymakers to invest in the hydroponics of peppers and other premium specialty crops (Goh et al., 2023).

Hydroponic Systems for Peppers

Pepper is a fruiting crop that responds well to hydroponic cultivation because the root zone can be kept stable in water, nutrients, oxygen, and pH. Among the commonly used systems, drip irrigation in containers or grow bags is often effective for peppers because it supports long-term crop growth and makes nutrient management easier. Research also indicates that the choice of substrate matters, with materials such as wood fibre, coir, and rockwool influencing root development and overall performance (Jung & Lee, 2023). Hydroponics helps peppers by improving nutrient uptake, reducing soil-borne disease pressure, and allowing better control of EC and pH in the root zone. This is especially useful for bell peppers, which are sensitive to nutrient imbalance and blossom-end rot when calcium and ammonium relationships are not well managed. Hydroponic systems also support more uniform fruiting and can be useful in protected cultivation or water-limited areas (Schnitzler et al., 2004). A low-tech drip system with containers or grow bags is a practical option for pepper growers because it is simpler to operate than fully recirculating systems. Research comparing multiple container systems found better plant growth and marketable yield in pot systems fitted with drippers than in some trough-based systems. For small-scale growers, substrate-based systems using coco coir or other inert media can also be attractive because they are easier to manage and buffer salinity better than some alternatives.

Nutrient management and solution formulation

Nutrient solution formulation for hydroponic pepper (*Capsicum annuum* L.) is a critical factor that balances fruit yield with nutritional quality. Research into fertilizer ratios has identified that formulations such as 5N-4.8P-21.6K and 5N-5.2P-21.6K are particularly effective for maximizing yield in sweet pepper cultivars like 'Orangella'(Singh et al., 2019). The electrical conductivity of these solutions serves as a primary management tool; maintaining an EC of 2.0 dS/m or higher has been shown to increase the concentration of bioactive compounds, including vitamin C, lycopene, and antioxidants, although it may lead to a slight decrease in overall fruit firmness and total yield(Preciado-Rangel et al., 2021). For certain niche cultivars, such as the 'Friariello' pepper, even higher EC levels around 4.4 mS/cm have been utilized to achieve superior antioxidant profiles(Amalfitano et al., 2017).

Advanced nutrient management also focuses on optimizing solution strength and replenishment strategies to improve sustainability and fruit marketability. Studies indicate that using a reduced-strength nutrient solution (60% concentration) in a closed system can actually increase marketable production by 15% by significantly reducing the incidence of blossom-end rot, while simultaneously improving water use efficiency by 32% (Giuffrida & Leonardi, 2012). In closed-loop systems, managing the rapid depletion of specific ions like potassium (K) and phosphate (P) is essential(Ahn & Son, 2022). Implementing alternative replenishment methods that stabilize these nutrient fluctuations allows closed-loop systems to achieve productivity and sugar content comparable to open-loop systems while drastically reducing the environmental impact of mineral runoff.

Environmental Control for Hydroponic pepper

A hydroponic system delivers water and nutrients to plant roots with extraordinary precision. But roots are only half the plant. Everything above the substrate the leaves that capture light, the flowers that set fruit, the stomata that regulate gas exchange lives in the aerial environment, and that environment is equally decisive for yield and quality. Light is where pepper production either begins or stalls. Every gram of fruit that a pepper plant produces starts as photons absorbed by chlorophyll, converted through photosynthesis into sugars, and allocated to growing tissue. Light is crucial not only for photosynthesis and carbon assimilation, but also for biomass production, plant yield, and the physiological and biochemical processes that shape fruit quality — making the lighting environment one of the most vital management levers in controlled environment agriculture (Lanoue et al., 2024). Pepper plants are demanding on this front. Unlike leafy greens, which thrive under moderate light intensities, peppers need strong, sustained illumination throughout their long fruiting season. Research on *Capsicum annuum* in vertical indoor farming conditions found that fruit yield and fruit number per plant increased at a light intensity of 500 μmol m^{-2} s^{-1} compared to 300 μmol m^{-2} s^{-1} confirming that higher photon flux density drives measurably better production outcomes in indoor pepper systems. At the same time, pepper plants are not unlimited light consumers (Wittmann et al., 2025). Pepper plants have shown yield reductions under excessively long photoperiods, indicating that photon exposure has a productive ceiling and that photoperiod management — not simply maximizing daily light — is essential for optimizing the full cultivation cycle from seedling to harvest.

Fruit quality, yield optimization, and post-harvest handling

In hydroponic pepper production, fruit quality, yield optimization, and post-harvest handling are closely linked to precise control of the root-zone environment, because research shows that stable nutrient delivery, balanced pH and EC, and suitable substrates improve plant growth, fruit set, and marketable yield while reducing disorders such as blossom-end rot. Yield can be optimized by using drip-based container systems or other well-managed substrate systems, since studies on hydroponic bell pepper report better growth and yield when irrigation and substrate conditions are matched to the crop's long fruiting cycle. Fruit quality is improved when calcium nutrition is maintained and excess salinity or ammonium stress is avoided, as these factors influence firmness, color development, and storage behavior of pepper fruits(Zhou et al., 2025). After harvest, peppers should be handled gently, rapidly cooled, and stored under suitable temperature and humidity to preserve firmness, reduce shriveling, and extend shelf life, because post-harvest quality is strongly affected by harvest maturity and careful handling practices. Overall, research suggests that hydroponic pepper systems can produce high-quality fruits with better consistency than soil-based cultivation when pre-harvest nutrient management is integrated with proper post-harvest care(Rajaseger et al., 2023).

Smart farming and Future innovations

Smart farming is shaping hydroponic pepper production through sensor-based monitoring, automation, and precision nutrient control, which help maintain stable pH, EC, temperature, and moisture in the root zone and improve yield consistency. Research on bell pepper hydroponics shows that low-tech drip systems with suitable substrates and slow-release fertilizers can still deliver strong growth, high marketable yield, and better fruit quality, while poor nutrient balance can increase blossom-end rot and non-marketable fruits (D. J. Rahman, n.d.). Future innovations are likely to focus on IoT-connected systems, automated irrigation, data-driven fertigation, and AI-supported decision making, all of which can make pepper production more efficient, water-saving, and climate-resilient. Another promising direction is the development of low-cost hydroponic structures for tropical and resource-limited regions, since studies have already shown that sweet pepper can perform well with simplified systems and optimized nutrient solutions. The research suggests that the future of hydroponic pepper lies in combining smart technologies with practical, affordable system design to improve yield, fruit quality, and sustainability(Goh et al., 2023). IoT sensors in hydroponic pepper monitoring are used to track the key root-zone and greenhouse conditions that directly affect growth, fruit set, and yield. Typical sensors measure pH, EC or TDS, nutrient-solution temperature, air temperature, humidity, and water level, and the data can be sent to a phone, dashboard, or cloud platform for real-time control. Research on IoT-based hydroponic systems shows that this sensor-driven approach supports automatic pumping and nutrient delivery, improves monitoring accuracy, and reduces manual work, which is especially useful for pepper crops that need stable conditions over a long growing period (K & A, 2024). In pepper production, these sensors help maintain the ideal nutrient balance, prevent stress, and detect problems early, such as low water level, high temperature, or unsuitable solution strength, which can reduce blossom-end rot and yield loss.

Conclusion

In conclusion, hydroponics offers a highly promising production model for peppers and premium specialty crops because it allows precise control over nutrients, water, and root-zone conditions, which directly supports better growth, higher yield, and improved fruit quality. Its ability to reduce soil-borne diseases, save water, and enable cultivation in limited spaces makes it especially valuable for modern horticulture and protected farming systems.

For specialty crops, hydroponics also opens new opportunities in year-round production, uniform quality, and market-oriented farming for high-value produce. With continued improvement in system design, automation, and crop-specific nutrient management, hydroponics can become a practical and profitable approach for growers seeking sustainable and premium crop production.

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Quality Protein Maize (QPM): Development, Nutritional Benefits and Utilization in Human and Animal Diet

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Maize (*Zea mays* L.) Is one of the most widely cultivated cereal crops globally, serving as a primary food source for hundreds of millions of people in developing nations. However, conventional maize suffers from a critical nutritional limitation: its endosperm protein is severely deficient in the essential amino acids lysine and tryptophan, resulting in poor protein quality and contributing to widespread protein-energy malnutrition (PEM). Quality Protein Maize (QPM) was developed through decades of breeding innovation, primarily leveraging the opaque-2 (o2) mutant gene along with endosperm modifier genes, to produce maize with two-fold higher levels of lysine and tryptophan compared to normal maize. QPM exhibits a biological value (BV) of approximately 80%, nearly comparable to egg protein and twice that of conventional maize (40–57%). The historical development of QPM, its genetic basis, nutritional composition, human health benefits particularly in combating kwashiorkor, pellagra and childhood malnutrition and its utilization in animal feeding systems including poultry, swine, and dairy.QPM represents a powerful, cost-effective biofortification strategy with the potential to dramatically improve nutritional security in maize-dependent populations worldwide.

Introduction

Maize (*Zea mays* L.) is the third most important cereal crop globally after wheat and rice, and it serves as a primary staple food for millions of people across Sub-Saharan Africa, Latin America, and parts of Asia. In many of these regions, maize constitutes a major portion of daily caloric intake. However, despite its importance as an energy source, the nutritional quality of maize protein is inherently poor. The endosperm protein of normal maize is dominated by zeins, a class of prolamine storage proteins that account for about 60% of total protein but are deficient in essential amino acids such as lysine and tryptophan. Notably, lysine content in conventional maize is only about 2% of total protein, which is significantly lower than recommended dietary requirements.

This imbalance in amino acid composition has serious nutritional consequences for populations that rely heavily on maize-based diets. Chronic consumption of such diets often leads to protein-energy malnutrition, particularly in children, resulting in conditions such as kwashiorkor, stunted growth, impaired cognitive development, and reduced immunity. Additionally, the poor balance between leucine and isoleucine in normal maize interferes with the body's ability to convert tryptophan into niacin (vitamin B3), thereby increasing the risk of pellagra. These health challenges highlight the urgent need to improve the nutritional quality of maize.

Efforts to address this limitation led to the identification of a naturally occurring genetic mutation known as *opaque-2 (o2)*, which significantly enhances lysine and tryptophan content in maize grains. However, early versions carrying this mutation were not suitable for cultivation due to undesirable traits such as soft, chalky kernels, lower yield, and increased susceptibility to pests and diseases. Through sustained breeding efforts, these limitations were overcome by incorporating modifier genes that restored kernel hardness and improved agronomic performance, leading to the development of Quality Protein Maize (QPM). These improved varieties combine enhanced nutritional quality with desirable agronomic traits, making them a promising solution to combat malnutrition. In India, significant progress has been made with the release of QPM varieties such as Shakti-1, marking an important step toward improving food and nutritional security.

Historical development of QPM

Key Milestones in QPM Development
1964: Mertz, Bates & Nelson discover opaque-2 (o2) mutant with elevated lysine & tryptophan (Mertz et al., 1964)
1965: Nelson et al. confirm o2 nutritional superiority in rat feeding trials
1969–1980s: CIMMYT initiates program to combine o2 with endosperm modifier genes
1990s: First hard-endosperm QPM varieties (modern QPM) successfully developed at CIMMYT
1997: India's DMR releases Shakti-1, first QPM composite variety in South Asia
2000: World Food Prize awarded to CIMMYT scientists Vasal & Villegas for QPM development
2010s: Molecular marker-assisted breeding accelerates QPM varietal development worldwide
2017: Pakistan releases first QPM hybrids (QPHM-200, QPHM-300) through CIMMYT–NARC collaboration
2020s: Combined QPM + provitamin A (PVA) biofortification approaches under active development

Genetic Basis of QPM

The opaque-2 gene encodes a transcription factor (bZIP protein) that normally activates the expression of zein storage protein genes in the maize endosperm. In the recessive o2 mutant, zein synthesis is substantially reduced, leading to a compensatory increase in non-zein proteins specifically lysine-rich albumins, globulins, and glutelin that are far richer in essential amino acids. This shift in protein composition results in a two-fold increase in lysine and tryptophan content compared to normal maize, along with increases in histidine, arginine, aspartic acid, and glycine.

The critical innovation that converted nutritionally superior but agronomically inferior opaque-2 maize into practical QPM was the identification and use of endosperm modifier genes. These modifier loci act epistatically to restore the vitreous, hard endosperm phenotype in o2 backgrounds. Multiple minor modifier QTLs distributed across the maize genome collectively convert the floury opaque endosperm into the hard semi-translucent type preferred by farmers and processors, without compromising the amino acid quality conferred by the o2 allele.

Nutritional Composition of QPM

The key nutritional difference between Quality Protein Maize (QPM) and normal maize lies in the type and quality of protein they contain. In normal maize, about 60% of the protein is **zein**, which is very low in essential amino acids like lysine and tryptophan. In QPM, the zein content is reduced to about 40%, while other protein fractions (albumins and globulins), which are rich in lysine and tryptophan, are increased. As a result, QPM contains about **60–100% more lysine and tryptophan** than normal maize.

Another important improvement is in the amino acid balance. QPM has a lower leucine-to-isoleucine ratio compared to normal maize. This is beneficial because it helps the body convert tryptophan into **niacin (vitamin B3)** more efficiently, reducing the risk of **pellagra**, a disease common in maize-based diets.

QPM also shows much better overall protein quality. Its **Biological Value (BV)** is around **80%**, compared to **40–57% in normal maize**, and is close to that of

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egg protein. Similarly, its **PDCAAS (Protein Digestibility-Corrected Amino Acid Score)** is much higher and meets international nutritional standards. In addition, QPM protein is more digestible and its availability is comparable to **casein (milk protein)**.

Table 1: Comparative Nutritional Profile of Normal Maize vs. Quality Protein Maize (QPM)

Parameter	Normal Maize (NM)	Quality Protein Maize (QPM)
Lysine (% protein)	~2.0	~4.0–4.5
Tryptophan (% protein)	~0.4	~0.8–0.9
Biological Value (%)	40–57	~80
Protein Digestibility	Moderate	Superior
Zein Fraction (%)	~60	~40 (reduced)
PDCAAS Score	Lower	Higher (near casein)
Pellagra Prevention	Poor	Effective

Combating Protein-Energy Malnutrition

The primary impetus for QPM development was the need to address protein-energy malnutrition (PEM) in communities where maize is the dominant food crop. Kwashiorkor a severe form of protein malnutrition characterized by edema, growth failure, and immune suppression is most commonly seen in children in maize-dependent communities of Sub-Saharan Africa and parts of Asia and Latin America. Clinical and community-based studies have confirmed that substituting QPM for normal maize in children's diets significantly improves growth rates, weight gain, and overall nutritional status (Akalu et al., 2010).

In Ethiopia, a study by Akalu et al. found a significant effect of QPM consumption on the weight gain of children from households that cultivated QPM, suggesting that QPM cultivation and consumption could reduce or prevent poor growth and even support catch-up growth in undernourished children. UNICEF has recognized QPM as an effective dietary intervention for combating malnutrition in maize-dependent communities.

Pellagra is a niacin (vitamin B3) deficiency disease historically associated with maize-based diets in populations without access to diverse foods. It presents as the classic 'three Ds': dermatitis, diarrhea, and dementia, along with many other symptoms including skin lesions, nerve damage, insomnia, and cardiomyopathy (Hegyi et al., 2004). The high leucine content of normal maize interferes with tryptophan conversion to niacin, exacerbating pellagra risk. QPM's reduced leucine-to-isoleucine ratio and doubled tryptophan content address both the niacin synthesis pathway and the direct amino acid deficiency, making QPM an effective dietary strategy for pellagra prevention (Maqbool et al., 2021).

Lysine plays an important role as a neurotransmitter precursor and in calcium absorption, bone development, and immune function. Tryptophan is a precursor to serotonin a key neurotransmitter and chronic tryptophan deficiency

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has been linked to cognitive disorders, aberrant behaviour, and impaired brain development in children. Regular QPM consumption can meaningfully improve lysine and tryptophan intake in high-risk populations pregnant women, lactating mothers, infants, and young children who are most vulnerable to deficiency impacts (Joshi et al., 2022). The QPM grain is also gluten-free, making it a suitable staple grain for populations with gluten intolerance.

Utilization of Maize in Animal Nutrition

Approximately 70% of global maize production is utilized in animal feeds, with roughly 50% of commercial poultry diets consisting of maize. Maize is favored in animal diets for its high energy content, low fiber, high palatability, and digestibility. However, the poor protein quality of normal maize particularly its lysine and tryptophan deficiency forces livestock producers to supplement diets with expensive protein concentrates (soybean meal, fishmeal) and synthetic amino acids, substantially increasing the cost of livestock production

Challenges in QPM Adoption

Despite its well-documented nutritional advantages and decades of breeding efforts, the adoption of Quality Protein Maize (QPM) by farmers and the food industry remains below its potential in many developing countries due to several interrelated constraints. One major limitation is the yield gap, as QPM varieties in some environments still exhibit slightly lower yields compared to elite non-QPM hybrids, reducing economic incentives for farmers. Additionally, seed production and maintenance pose challenges because the *opaque-2 (o2)* gene is recessive and not visibly distinguishable in heterozygous conditions, making it difficult to maintain genetic purity; this necessitates strict isolation of QPM seed fields from normal maize to avoid cross-pollination and quality deterioration. Market-related issues further hinder adoption, including low consumer and processor awareness of QPM's nutritional benefits and the absence of a price premium, which weakens demand. Moreover, QPM varieties have lagged behind in developing tolerance to biotic stresses such as ear rot, grey leaf spot, and *Striga*, as well as abiotic stresses like drought, heat, and low soil nitrogen, limiting their adaptability in marginal environments. Finally, post-harvest challenges also contribute to the adoption gap, as the altered endosperm protein composition in QPM can sometimes increase susceptibility to storage pests and aflatoxin contamination.

Conclusion

Quality Protein Maize (QPM) stands as one of the most important achievements in applied plant nutrition and crop improvement of the twentieth century. By combining the *opaque-2* mutation with endosperm modifier genes, breeders successfully converted a nutritionally superior but agronomically weak maize type into a high-yielding, farmer-acceptable crop with hard, vitreous kernels. This innovation enabled QPM to deliver protein quality approaching that of animal-based foods while retaining all the advantages of a cereal crop. With a biological value of around 80% and nearly double the levels of essential amino acids such as lysine and tryptophan compared to normal maize, QPM significantly enhances dietary protein quality. Importantly, it remains fully compatible with traditional and modern processing methods, making it easy to integrate into existing food systems.

The nutritional benefits of QPM are especially evident in human health, where its consumption has been associated with reduced incidence of protein-energy malnutrition, including conditions such as kwashiorkor and pellagra, particularly among vulnerable groups like children and pregnant or lactating women. In addition to its role in human diets, QPM also provides advantages in animal nutrition by improving protein efficiency in monogastric livestock and reducing reliance on expensive protein supplements. Looking ahead, continued progress in breeding, stronger market

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linkages, and increased awareness among consumers can further enhance QPM adoption. When combined with traits such as stress tolerance and additional biofortification, QPM has the potential to make a substantial and lasting contribution to global food and nutritional security.

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Morphological Abnormalities in Strawberry Fruits and Their Management

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Strawberries (*Fragaria* × *ananassa*) are a fruit crop of great economic importance because they are appreciated for their special characteristic flavour, vivid colour, and bioactive compounds with health benefits. The acceptance of strawberry fruits and their marketability largely depend on the post-harvest quality and shape. Strawberry cultivation, is often associated with fruit defects resulting in poorly shaped and underdeveloped berries. Such defects mainly occur due to poor aperiodic rainfall, lesser availability of suitable pollinators, nutritional deficiency, pest infestation and physiological abnormalities in the plant. Such irregular fruits not only reduce visual appeal but also decrease market price and profitability. Proper orchard management and suitable cultural practices can help minimise these abnormalities.

Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) is commonly cultivated across the world as a high-value fruit crop. It belongs to the family Rosaceae and is popular because of its attractive red colour, gentle aroma, sweet taste, and nutritional richness. Uniform fruit shape is considered one of the most important quality characteristics in strawberry marketing. Consumers generally prefer berries that are well-shaped, symmetrical, and evenly ripened. During cultivation, several internal and external factors may interfere with normal fruit growth, resulting in malformed berries. These fruits may become distorted, flattened, uneven, or underdeveloped. Fruit deformities are commonly observed under stressful growing conditions and can significantly affect both yield and fruit quality.

Major Causes of Fruit Deformity in Strawberry

- **Inadequate Pollination:** Proper pollination is essential for uniform berry formation in strawberries. Each achene present on the fruit surface must be fertilised for complete fruit development. When pollination remains incomplete, certain portions of the fruit fail to enlarge, resulting in an irregular berry shape.
- **Temperature Stress:** Very low or excessively high temperatures during flowering adversely affect pollen viability and fertilisation. As a result, fruit growth becomes uneven and malformed berries are produced.
- **Frost Damage:** Exposure to frost during bloom development can injure flower tissues, especially pistils and stamens. Damaged flowers often develop into distorted fruits with poor shape.
- **Nutritional Disorders:** Improper nutrient supply affects plant growth and fruit formation. Deficiency of micronutrients such as boron and an imbalance in nitrogen application may lead to abnormal berry development.
- **Hormonal Disturbances:** Plant hormones regulate cell division and enlargement during fruit growth. Any imbalance in growth regulators may interfere with normal development and produce misshapen fruits.
- **Insect and Disease Incidence:** Certain insects, including thrips and mites, feed on flowers and young fruits, causing physical injury and

deformities. Viral and fungal infections may also disrupt normal fruit growth.

- **Fasciation and Genetic Factors:** Some deformities occur due to fasciation, where floral tissues become fused or flattened. In certain cultivars, genetic characteristics may also contribute to irregular fruit shape.

Symptoms of Deformed Strawberry Fruits

The following symptoms are generally observed in malformed berries:

- Uneven or asymmetrical fruit shape
- Flattened or twisted berries
- Fan-like or fused fruits
- Poorly developed fruit portions
- Uneven colouration during ripening
- Small-sized or irregular berries
- Rough and unattractive fruit appearance

Impact on Strawberry Cultivation

Fruit deformities can create several problems in commercial strawberry production:

- Reduction in fruit quality and attractiveness
- Lower consumer preference and market demand
- Difficulty during sorting, grading, and packaging
- Increased chances of post-harvest spoilage
- Decrease in overall farm income

Preventive and Management Measures

The occurrence of malformed fruits can be reduced through proper management practices such as:

- Promoting effective pollination by maintaining bee activity in the field.
- Protecting crops from frost and extreme temperature fluctuations.
- Applying balanced fertilisers based on soil and crop requirements.
- Using healthy and certified planting materials.
- Maintaining proper irrigation and field hygiene.
- Monitoring and controlling pests and diseases regularly.
- Selecting cultivars suitable for local climatic conditions.
- Providing favourable environmental conditions during flowering and fruit set.

Conclusion

Abnormal fruit development is a common physiological problem in strawberry cultivation that greatly affects fruit appearance and marketability. Factors such as poor pollination, climatic stress, nutrient imbalance, pest attack, and hormonal irregularities are mainly responsible for fruit deformities. Adoption of scientific cultivation methods, balanced nutrition, and proper environmental management can effectively reduce the incidence of malformed fruits. Improving fruit quality through proper management practices ultimately enhances productivity and profitability in strawberry farming.

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Insects in a Changing World: From Extraordinary Diversity to Alarming Decline

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Insects constitute the most diverse and ecologically dominant group of organisms on Earth, playing indispensable roles in pollination, biological control, decomposition, nutrient cycling, and maintenance of ecosystem stability. India alone harbours nearly 7.1% of the world's recorded insect fauna, reflecting its immense ecological richness. However, increasing evidence suggests alarming declines in insect abundance, biomass, and diversity across natural and agricultural ecosystems due to habitat destruction, deforestation, urbanization, pesticide misuse, climate change, pollution, and invasive species. Such declines threaten food security, ecological resilience, biodiversity conservation, and rural livelihoods dependent on insect-mediated ecosystem services. This article highlights the extraordinary diversity and importance of insects, discusses the major drivers responsible for their decline, and emphasizes the urgent need for sustainable conservation strategies to safeguard insect biodiversity in a rapidly changing world.

Introduction

Biological diversity refers to the variability among living organisms from terrestrial, aquatic, and marine ecosystems, including diversity within species, between species, and among ecosystems (Convention on Biological Diversity, 1992). Among all living organisms, insects dominate the biosphere and represent nearly 75-80% of known animal species globally, with estimates ranging from 10 to 30 million species, although only around 1.1-1.7 million species have been scientifically described (Gebremariam, 2024).

The extraordinary success of insects is largely attributed to several evolutionary innovations such as exoskeleton development, articulated appendages, flight evolution, phytophagy, and complete metamorphosis, which enabled them to colonize almost every ecological niche on Earth (Gebremariam, 2024). Globally, insect biodiversity is concentrated mainly within four major orders namely Coleoptera, Lepidoptera, Hymenoptera, and Diptera, together accounting for nearly 70% of described insect species (Stork, 2018). Coleoptera alone contributes nearly 40% of known insect diversity with over 400,000 described species worldwide. India, recognized as one of the world's mega-diverse countries, supports approximately 63,760 described insect species representing nearly 7.1% of the world's insect fauna (Shashank *et al.,* 2022). Recent discoveries of new beetle species such as *Maladera champhaiensis* and *Serica subansiriensis* from northeastern India further indicate that the country's insect biodiversity remains vastly underexplored (PIB, 2025).

Despite their extraordinary diversity and ecological significance, insect populations across the world are now facing unprecedented declines. Scientists increasingly describe this phenomenon as the "insect apocalypse," reflecting alarming reductions in insect abundance, biomass, and species richness across multiple ecosystems (Saunders *et al.,* 2025). The decline of insects is emerging as a serious

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environmental concern with profound ecological, agricultural, and economic implications.

Ecological and Economic Importance of Insects

Insects are indispensable providers of ecosystem services that sustain both natural ecosystems and agricultural production systems. Pollinating insects such as bees, butterflies, moths, beetles, and hoverflies play vital roles in the reproduction of flowering plants and crops. Nearly 75% of globally important crop species depend partially or entirely on animal pollination, much of which is performed by insects (Wagner, 2020).

Figure 1. Insects contribute significantly to pollination, nutrient cycling and maintenance of ecosystem stability.

In addition to pollination, insects contribute immensely to nutrient cycling and decomposition. Dung beetles, often referred to as "biowaste managers" of nature, recycle organic matter, regulate parasites, and improve soil fertility (Maldonado *et al.,* 2019; Shah & Shah, 2022). With global waste generation increasing rapidly, insects such as black soldier fly, mealworm, and wax moth are now being explored for sustainable organic waste management and bioconversion systems (FAO, 2020). Predators and parasitoids act as natural pest regulators and form the backbone of biological control systems in agriculture (Daniel et al., 2020). Ladybird beetles, lacewings, dragonflies, predatory bugs, parasitic wasps, and spiders help suppress pest populations and reduce pesticide dependency in agroecosystems.

Economically, insect-based industries contribute significantly to rural livelihoods and national economies. India's sericulture industry supports more than 9.76 million people across nearly 52,000 villages and contributes substantially to rural employment and export earnings (ISEPC, 2023). Similarly, lac cultivation centered around *Kerria lacca* provides substantial income opportunities for tribal and smallholder communities. Studies from Assam reported average earnings of ₹83,050 per bigha with a benefit-cost ratio of 5.33 from lac cultivation (Maibangsa *et al.,* 2023).

Insects additionally contribute to medicine and scientific research. Indigenous communities in Nagaland practice entomotherapy, using insects and insect-derived products for treatment of respiratory disorders, skin infections, and other ailments (Mozhui *et al.,* 2021). Insects also serve as model organisms in genetics, physiology, and biotechnology. Species such as *Drosophila melanogaster* and *Bombyx mori* have significantly advanced biological and medical sciences (Giansanti & Piergentili, 2025; Ashraf & Qamar, 2023).

Table 1. Major Ecosystem Services Provided by Insects

Ecosystem Service	Major Insect Groups	Importance
Pollination	Bees, butterflies, hoverflies	Crop production and biodiversity
Biological control	Ladybird beetles, parasitoids, lacewings	Natural pest suppression
Decomposition	Dung beetles, termites, flies	Nutrient recycling and soil fertility
Soil	Ants, termites	Soil aeration

engineering		and organic matter mixing
Commercial products	Silkworms, lac insects, honey bees	Silk, lac, honey, beeswax

Growing Evidence of Insect Decline

During the last few decades, mounting scientific evidence has revealed substantial declines in insect populations worldwide. Long-term monitoring studies indicate alarming reductions in insect abundance, biomass, and diversity across forests, grasslands, freshwater ecosystems, and agricultural landscapes (Saunders *et al.,* 2025).

The International Union for Conservation of Nature (IUCN) has increasingly categorized numerous insect species as threatened or endangered. Recent assessments indicate that nearly 14% of Europe's dragonflies, 11% of saproxylic beetles, and 9% of butterflies face extinction risks (IUCN, 2023). Globally recognized insects such as the monarch butterfly (*Danaus plexippus*) and the Suckley cuckoo bumblebee (*Bombus suckleyi*) are now symbols of the growing biodiversity crisis (IUCN, 2014; IUCN, 2023).

In tropical ecosystems, the actual magnitude of insect decline may be even greater because many insect groups remain poorly studied. Tropical forests contain immense insect diversity, yet long-term ecological monitoring remains limited in many developing countries.

Habitat Loss and Deforestation

Habitat degradation remains one of the most serious threats to insect biodiversity globally (Foley *et al.,* 2011; Díaz *et al.,* 2019). Deforestation, land-use change, mining, infrastructure expansion, and agricultural intensification have fragmented natural ecosystems and disrupted ecological interactions essential for insect survival.

According to the Global Forest Resources Assessment (2020), global forest loss averaged nearly 10 million hectares annually between 2015 and 2020. India alone lost approximately 38.5 thousand hectares of tropical forest during 2019–2020. Such habitat destruction severely affects specialist insects dependent on diverse host plants and stable microhabitats.

Sharp *et al.* (2019) reported that tropical logging and forest fragmentation significantly reduce insect richness, particularly among wood-boring weevils and forest specialists. Fragmented habitats also isolate insect populations, increasing local extinction risks and reducing genetic diversity.

Urbanization, Light Pollution, and Environmental Stress

Rapid urbanization is increasingly altering insect communities worldwide. Urban landscapes replace natural vegetation with concrete infrastructure, reducing floral resources, nesting sites, and ecological connectivity. Long-term monitoring studies from rapidly urbanizing Chinese landscapes revealed declines exceeding 80% in farmland pest abundance over 17 years due to habitat alteration and land-use change (Wan et al., 2025).

Urban ecosystems often favour disturbance-tolerant generalist species while sensitive pollinators, parasitoids, and specialist insects decline (Corcos et al., 2019). Artificial light pollution has emerged as another major driver affecting nocturnal insects. Light pollution disrupts navigation, mating behaviour, feeding activity, and circadian rhythms of moths, beetles, and other nocturnal pollinators (Van de Schoot *et al.,* 2025).

Environmental pollution, including chemical contaminants and microplastics, further affects insect physiology, reproduction, and survival.

Pesticides and Agricultural Intensification

The intensification of modern agriculture has significantly contributed to insect decline.

Indiscriminate pesticide use not only targets pests but also destroys beneficial insects including pollinators, decomposers, predators, and parasitoids. Repeated pesticide applications often create ecological imbalances, pest resurgence, and resistance development.

In India, recurrent whitefly outbreaks in cotton ecosystems have been linked to excessive pesticide applications and evolution of resistant pest genotypes (Kumar *et al.,* 2025). Herbicide use additionally reduces weed diversity, eliminating nectar and pollen resources needed by beneficial insects.

Agricultural simplification through monoculture systems also reduces habitat heterogeneity and floral diversity essential for maintaining insect populations.

Climate Change and Emerging Challenges

Climate change is increasingly influencing insect distribution, phenology, and ecological interactions. As ectothermic organisms, insects are highly sensitive to temperature fluctuations and environmental changes (Mukhtar *et al.,* 2023). Rising temperatures, altered rainfall patterns, prolonged droughts, floods, and extreme climatic events are reshaping insect communities globally.

Climate change can disrupt synchrony between insects and flowering plants, affecting pollination services and ecosystem stability. At the same time, warming conditions may facilitate expansion of invasive pests and disease vectors into new geographical regions. In India, climate linked changes in pest outbreaks and invasions are increasingly reported from agricultural ecosystems (Mukhtar *et al.,* 2023).

The combined effects of climate change and habitat degradation may severely threaten tropical insect diversity in coming decades.

Table 2. Major Drivers Responsible for Global Insect Decline

Driver	Impact on Insects
Habitat destruction	Loss of nesting and feeding habitats
Pesticide misuse	Mortality of pollinators and beneficial insects
Climate change	Altered distribution and phenology
Light pollution	Disrupted mating and navigation
Urbanization	Habitat fragmentation
Invasive species	Competition and ecological imbalance

Conservation Strategies and Future Directions

Addressing insect decline requires integrated scientific, ecological, agricultural, and policy-based interventions. Habitat restoration through afforestation, wetland conservation, ecological corridors, and native vegetation planting can significantly improve insect diversity. Reducing agrochemical dependency, redesigning sustainable agricultural systems, and strengthening biodiversity conservation policies are considered essential for long-term insect conservation (Raghavendra *et al.,* 2022). Ecosystem specific conservation approaches such as maintaining vegetation diversity and promoting indigenous plants in urban and agricultural landscapes can also significantly enhance insect biodiversity and ecological resilience (Samways et al., 2020).

Several recent conservation initiatives have demonstrated encouraging results under field conditions. In Tamil Nadu, the introduction of floral intercrops such as marigold and red gram in moringa fields increased pollinator abundance by nearly 50%

and fruit set by about 30%, simultaneously improving biodiversity conservation and farmer income (Dhandapani *et al.,* 2023). Similarly, conversion of roadside exotic shrubs into native wildflower meadows in Germany enhanced arthropod abundance by more than 200%, highlighting the ecological importance of native vegetation restoration (Mata *et al.,* 2021).

India's first Pollinator Park established in Haldwani, Uttarakhand, represents another important initiative integrating conservation, ecological restoration, public awareness, and pollinator protection. In addition, citizen science programs, butterfly monitoring campaigns, pollinator gardens, biodiversity parks, and school level environmental education initiatives can play crucial roles in strengthening long-term insect conservation efforts and promoting ecological awareness among future generations.

Conclusion

Insects are among the most vital components of Earth's biodiversity and ecological functioning. Their contributions to pollination, biological control, decomposition, nutrient cycling, waste management, and scientific advancement make them indispensable for both natural ecosystems and human wellbeing. However, increasing habitat destruction, pesticide misuse, urbanization, climate change, pollution, and invasive species are driving alarming declines in insect populations worldwide.

The decline of insects represents not only a biodiversity crisis but also a serious threat to agricultural sustainability, food security, and ecosystem resilience. Conserving insect diversity therefore requires urgent and coordinated action involving science, policy reforms, sustainable agriculture, habitat restoration, and public participation. Protecting insects today is essential for ensuring ecological stability and environmental sustainability for future generations.

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Micronutrients & their critical limits in soils and plants

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Critical limits of deficiency of micronutrients in soils and plants are usually employed to advice on need of micronutrient fertilization. The aim of good nutrition plan is to keep all nutrients at the optimum level. Below the optimum concentration, conditions start developing into deficiency and above the optimum towards wasteful and then toxic levels. The soil critical level established for Zn,Cu,Fe,Mn,B,Mo and S were 0.6, 0.2, 4.0, 2.0, 0.5,0.2 and 10.0mg kg-1, respectively. Diagnosis and prevention of nutrient deficiency and toxicity requires a further knowledge of symptomology with critical value of any particular element in plants too.

Introduction

Green revolution has greatly increased the crop production in India, but continuous cultivation of high yielding crop varieties have led to depletion of native micronutrient soil fertility and now most of the soils are showing sign of fatigue for sustaining higher crop production. World over micronutrients gaining much importance not only for their role in sustaining higher crop yields but such increased nutritional deficiency in soil and seed is more affecting plant, animal and human health. Deficiency of Zn, Fe, Cu, Mn, B, Mo and S has been noticed in 48, 12, 4, 5, 33, 13 and 41 % of soils of India, respectively. Zinc deficiency in soils is further expected to increase from 49 to 63 % by the year 2025 as most of the marginal soils are being brought under cultivation. Besides this, hidden hunger of micronutrients is widely noticed leading to even entire failure of crops and reduced content of micronutrients in plant parts (Singh and Bahera, 2007). Historically, no special efforts were made to supply secondary and micronutrients since these got added through other nutrient sources either as adjacent radicals or as contaminants or supplied through organic manures. With intensification of agriculture, usage of straight fertilizers and rising crop requirements due to increasing productivity levels, have heightened the secondary and micron utrient demand in soil fertility management and are increasingly becoming major constraint to achieve increased agricultural production including cereal and oil seed crops (Joshi *et al*., 2000).

Critical limits of micronutrients in soil

Soil micronutrient availability is largely dictated by soil pH, organic matter and texture. The following table highlights generally accepted critical limits using DTPA (Diethylenetriaminepentaacetic acid) and hot water extractable.

Critical levels of micronutrients in soils greatly accepted in India are given in Table 1. The soil critical established for Zn, Cu, Fe, Mn, B, Mo and S were 0.6, 0.2, 4.0, 2.0, 0.5, 0.2 and 10.0 mg kg-1, respectively.

Micronutrients for critical limits of soil are :

Zinc (Zn)

Zinc deficiency affects more than half of global cereal-growing soils and is arguably the most widespread and economically important micronutrient disorder in world agriculture.

Iron (Fe)

Iron is the fourth most abundant element in the Earth's crust, yet iron deficiency chlorosis is one of the most prevalent micronutrient disorders in agriculture globally.

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Copper (Cu)

Copper has one of the narrowest sufficiency windows of all micronutrients.

Manganese (Mn)

Manganese deficiency is widespread in coarse-textured, well-drained, high-pH soils, while toxicity is common in strongly acidic soils.

Boron (B)

Boron is unique among micronutrients in that it occurs in soil predominantly as the uncharged molecule boric acid [$B(OH)_3$], which is extracted by hot water.

Molybdenum (Mo)

Molybdenum is required in the smallest amounts of any essential micronutrient.

Sulphur (S)

While sulphur is classified as a secondary macronutrient rather than a micronutrient, it is critical for plant health.

Table : 1 Critical levels of deficiency of micronutrients in soils usually adopted in India

Nutrient	Extractant	Critical level ($Mg\ kg^{-1}$)
Zn	DTPA	0.4-1.2 (0.6)
Fe	DTPA	2.5-4.5
Fe	Ammonium acetate	2.0
Cu	DTPA or ammonium acetate	0.2
Mn	DTPA	2.0
B	Hot water	0.5
Mo	Ammonium oxalate	0.2
S	0.15% Cacl2 2h2O	10

Critical limits of micronutrient in plants

Plant critical levels are based on the nutrient concentration in recently matured leaves or whole shoots. When levels fall below these ranges, plants typically display visible deficiency symptoms (e.g., chlorosis, stunted growth). A given critical limit is quite often employed for a wide variety of soils and crops, even though it is known that these critical limits may differ not only for soils and crop species but also for different varieties of a given crop. Commonly found concentrations of micronutrients in plant tissue are provided in Table 2

Micronutrients & their critical limits of plants tissue are :

Boron (B)

Boron functions in cell wall structural integrity, membrane function, and reproductive development.

Copper (Cu)

Copper is required for photosynthetic electron transport, lignification, and the enzyme superoxide dismutase.

Iron (Fe)

The critical deficiency concentration of Fe in plant tissue (youngest mature leaf) is approximately 50 mg kg^{-1} dry weight (DW), with the sufficiency range spanning 100–500 mg kg^{-1} DW.

Molybdenum (Mo)

Molybdenum is the micronutrient required in the smallest quantity by plants. Critical deficiency in mature leaves is below 0.1 mg Mo kg^{-1} DW, sufficiency between 0.1 and 1.0 mg kg^{-1} DW, and toxicity above 10 mg kg^{-1} DW

Zinc (Zn)

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Zinc is an essential co-factor of over 300 enzymes and indirectly regulates the biosynthesis of auxin and chlorophyll

Chlorine (Cl)

Chlorine (taken up as the chloride ion, (Cl^-) is an essential micronutrient vital for osmosis, turgor regulation, and photosynthesis.

Table : 2 Micronutrient concentrations in plant

Micronutrient	Concentration dry matter basis	Remarks
Boron	2-100 ppm	Usually 20 ppm, much higher in dicots (legumes) than in monocots (cereals etc)
Copper	5-20 ppm	Usually, less than 5-20ppm
Iron	50-150 ppm	usually 100 ppm
Molybdenum	0.1-2 ppm	usually below 1 ppm
Zinc	20-100 ppm	Usually 20-50 ppm
Chlorine	0.2-2%	Much above the actual required

Conclusion

Micronutrient critical limits in soil and plants represent quantitative thresholds that are foundational to modern soil fertility management and precision agriculture. The sufficiency ranges for Fe, Mn, Zn, Cu, B, Mo, Cl, and S in both soil extractant and plant tissue have been established through decades of agronomic research, and while the general frameworks are well-established, considerable nuance surrounds their application in practice. Soil pH, organic matter, redox conditions, crop species, and nutrient interactions all modulate the effective availability and critical concentrations of micronutrients, necessitating contextual interpretation of analytical results.

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Digital Agricultural Extension Transforming the Future of Smart Farming

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Digital Agricultural Extension is the use of information and communication technologies (ICT) like mobile phones, artificial intelligence, and remote sensing to deliver personalized, real-time farming advice, market data, and weather forecasts directly to farmers, and it's emerging as a revolutionary approach for transforming traditional farming systems into smart and sustainable agricultural systems. The integration of Information and Communication Technologies (ICTs), Artificial Intelligence (AI), Internet of Things (IoT), remote sensing, mobile applications, drones, and big data analytics has significantly improved the efficiency of agricultural advisory services. Digital agricultural extension helps providing real-time, location-specific, and demand-driven information directly to farmers through digital platforms. Smart farming technologies enable farmers to make informed decisions regarding crop management, irrigation scheduling, pest and disease control, weather forecasting, and market intelligence. Mobile-based advisory services, Artificial intelligence (AI), Drone Technology, Remote Sensing, Social media platforms are helping farmers access scientific knowledge quickly and effectively. The use of digital extension services for smart farming to contributes sustainable agriculture by reducing resource wastage, increasing crop productivity, improving climate resilience, and enhancing market connectivity. This article discusses the concept of digital agricultural extension and their emerging paradigm, key features of digital agricultural extension, key components of digital agricultural extension, applications of digital agricultural extension in smart farming, benefits of digital agricultural extension and future prospects of digital agricultural extension in smart farming. It highlights how digital agricultural extension technologies are transforming the future of smart farming.

1. Introduction

Agriculture is the backbone of the economy in many developing countries, especially in India. Farmers today face numerous challenges such as climate change, declining soil fertility, water scarcity, pest outbreaks, market fluctuations, and labour shortages. Traditional agricultural extension systems have played an important role in transferring agricultural technologies to farmers; however, they often struggle to meet the growing demands of modern agriculture.

The rapid advancement of digital technologies has created new opportunities for improving agricultural productivity and sustainability. Digital Agricultural Extension refers to the use of digital tools and communication technologies to provide agricultural information, training, and advisory services to farmers.It combines modern technologies such as smartphones, internet services, mobile applications, Artificial Intelligence (AI), Internet of Things (IoT), drones, satellite imaging, cloud computing, and data analytics to support smart farming practices. Smart farming uses advanced technologies to optimize agricultural operations and improve decision-making. Digital extension systems provide timely information related to weather forecasting, soil health, crop management, disease diagnosis, irrigation scheduling, and market prices. These technologies help farmers for smart farming as a

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increase productivity, reduce costs, and enhance profitability.

Digital Agricultural Extension is becoming an important pillar of smat farming, sustainable and climate-smart agriculture. It not only improves agricultural efficiency but also empowers farmers with knowledge, skills, and market opportunities.

2. Concept of Digital Agricultural Extension:

Digital Agricultural Extension is the use of digital technologies such as mobile apps, SMS, AI, and video to deliver farming advice, market information. It modernizes traditional agricultural outreach, helping farmers make faster, data-driven decisions for smart farming i.e. increase productivity and sustainability. Digital Agricultural Extension is the application of digital technologies for delivering agricultural advisory services, training, and information to farmers through electronic platforms.

3. Digital Agricultural Extension: An Emerging Paradigm:

Digital Agricultural Extension is an emerging approach that uses digital technologies to provide timely agricultural information, advisory services, and knowledge transfer to farmers. It improves communication between farmers, extension workers, researchers, and markets, making farming more efficient, informed, and technology-driven.

3. 1 Key Features of Digital Agricultural Extension:

- Real-time dissemination of agricultural information
- Use of mobile phones, internet, drones, remote sensing, IoT.
- Quick advisory services for pest, disease, and weather management
- Better farmer–expert interaction through digital communication
- Improved access to market prices and modern technologies

3.2 Digital Tools Used:

- Mobile applications
- Social media platforms such as WhatsApp and YouTube
- Drones, sensors, and AI-based advisory systems

Example:

A farmer receives weather alerts and pest management advice through a mobile app. By watching crop management videos on YouTube and joining farmer groups on WhatsApp, the farmer learns modern cultivation techniques and takes timely decisions, resulting in increased crop productivity and reduced losses.

4. Key Components of Digital Agricultural Extension:

1. Mobile-Based Advisory Services:

Mobile phones are widely used for disseminating agricultural information through SMS, voice calls, mobile apps, and WhatsApp groups.

ISSN: 3049-2289

Examples:

- Kisan Suvidha App
- mKisan Portal
- IFFCO Kisan App

Benefits:

- Quick dissemination of information
- Weather updates and market prices
- Pest and disease management guidance.

2. Artificial Intelligence in Smart Farming:

Artificial Intelligence helps farmers analyze large amounts of agricultural data for decision-making.

Applications:

- Crop disease detection
- Yield prediction
- Smart irrigation systems
- Precision fertilizer application.

Example:

AI-powered applications can identify plant diseases from leaf images and suggest suitable control measures instantly.

3. Internet of Things (IoT):

IoT devices collect real-time farm data through sensors installed in fields.

Functions:

- Soil moisture monitoring
- Temperature and humidity sensing
- Automated irrigation management

Data Example:

Studies show that IoT-based irrigation systems can reduce water usage by 30–50% while increasing crop productivity.

4. Drone Technology:

Drones are increasingly used for monitoring crop growth, spraying pesticides, and assessing field conditions.

Advantages:

- Rapid field surveillance, Reduced labour costs and Precision spraying

Example:

Drone-based pesticide spraying can reduce chemical usage by approximately 20–30%.

5. Remote Sensing and GIS:

Remote sensing technologies use satellite imagery and Geographic Information Systems (GIS) for agricultural monitoring.

Uses:

- Crop health assessment
- Drought monitoring
- Land use mapping
- Weather forecasting

ISSN: 3049-2289

5. Applications of Digital Agricultural Extension in Smart Farming:

1. Weather Forecasting and Climate Advisory:

Mobile applications provide real-time weather forecasts, rainfall predictions, temperature information, and climate advisories that help farmers plan agricultural operations efficiently and also help farmers adapt to climate variability through weather forecasting and early warning systems.

Example:

The Kisan Suvidha mobile application developed by the Government of India provides weather updates, agro-advisories, and extreme weather alerts to farmers.

Benefits:

- Scientific crop planning
- Reduced climate-related risks
- Better irrigation scheduling
- Improved crop protection measures

2. Smart Irrigation and Water Management:

Mobile applications integrated with IoT devices and soil moisture sensors assist farmers in efficient irrigation management.

Example:

Smart irrigation applications connected with sensor-based irrigation systems provide alerts regarding soil moisture levels and irrigation scheduling.

Applications:

- Automated irrigation scheduling
- Water requirement estimation
- Soil moisture monitoring
- Precision water management

Benefits:

- Water conservation
- Reduced irrigation costs
- Improved water-use efficiency
- Sustainable agriculture

3. Pest and Disease Management:

Mobile applications equipped with Artificial Intelligence (AI) and image recognition technologies help farmers identify crop diseases and pest infestations through smartphone photographs.

Example:

IFFCO Kisan provides pest and disease management recommendations, expert advisory services, and crop protection guidance in regional languages.

Applications:

- Early disease diagnosis and Pest outbreak alerts
- Crop protection recommendations and Scientific pesticide usage

Benefits:

- Reduced crop losses
- Lower pesticide misuse
- Increased crop productivity
- Timely advisory services

ISSN: 3049-2289

4. Crop Advisory and Farm Management:

Mobile applications provide complete crop management guidance including seed selection, fertilizer recommendations, sowing time, harvesting methods, and crop calendars.

Example:

AgriApp delivers crop-wise advisory services, farm management information, and expert consultation for farmers.

Applications:

- Crop production guidance
- Nutrient management
- Farm activity planning
- Expert consultation

Benefits:

- Scientific farming practices
- Increased productivity
- Better farm management
- Reduced production costs

5. Market Information Services:

Digital platforms provide farmers with updated market prices and marketing opportunities.

Examples:

- eNAM (National Agriculture Market)
- AgriMarket App

Impact:

Farmers receive better prices through transparent digital marketing systems.

6. Benefits of Digital Agricultural Extension:

a. Timely Information Delivery:

Farmers receive instant updates related to weather, pests, diseases, and markets.

b. Wider Outreach:

Digital platforms can reach millions of farmers simultaneously.

c. Cost-Effective Communication:

Mobile and online advisory services reduce extension costs.

d. Improved Decision-Making:

Real-time data helps farmers make scientific farming decisions.

e. Increased Productivity:

Smart farming technologies improve crop yield and resource efficiency.

f. Better Farmer Empowerment:

Digital literacy improves farmers' knowledge and confidence.

7. Future Prospects of Digital Agricultural Extension:

The future of digital agricultural extension is highly promising. Emerging technologies such as block chain, robotics, machine learning, big data analytics, and cloud computing are expected to further transform agriculture.

Future Trends:

- AI-powered personalized advisory services
- Smart greenhouses
- Autonomous farm machinery
- Blockchain-based supply chains
- Real-time crop monitoring systems

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Governments, universities, research institutions, and private companies are increasingly investing in digital agriculture to improve food security and rural livelihoods.

Conclusion:

Digital Agricultural Extension is transforming the future of smart farming by integrating modern digital technologies into agricultural advisory systems. Technologies such as Artificial Intelligence, IoT, drones, mobile applications, remote sensing, and social media are improving agricultural productivity, sustainability, and farmer empowerment. Digital platforms provide timely and accurate information that helps farmers make better decisions related to crop production, irrigation, pest management, and marketing.

The adoption of digital agricultural extension services has significantly enhanced communication between farmers, scientists, extension workers, and markets. It contributes to climate-smart and precision agriculture while reducing production costs and environmental impacts. Ultimately digital agricultural extension plays a vital role in achieving sustainable agricultural development and food security through smart farming.

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ISSN: 3049-2289

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Assessment of Genetic Variability, Heritability and Genetic Advance Among Advanced Breeding Lines of Groundnut (*Arachis hypogea* L.)

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A Field experiment with 30 advanced breeding lines of groundnut was carried out for assessment of genetic variance, heritability (broad sense) and genetic advance as per cent of mean for 17 metric traits. The analysis of variance revealed the existence of highly significant differences among the entries for all the characters studied. The phenotypic coefficient of variation (PCV) was greater than genotypic coefficient of variation (GCV) for all the traits studied implying that these characters were highly influenced by the environmental effects. High PCV and GCV values (>20%) was recorded for Pod yield plant^{-1}, Kernel yield plant^{-1}, dry haulms yield plant^{-1} and number of mature pods plant^{-1}. High heritability (> 60%) coupled with high genetic advance as per cent of mean was registered for plant height, hundred pod weight, kernel yield plant^{-1}, dry haulms yield plant^{-1}, number of primary branches plant^{-1}, number of mature pods plant^{-1}, harvest index and pod yield plant^{-1} indicating that these characters were governed by additive gene effects and could be chosen as selection criteria for formulating breeding strategies in groundnut.

1. Introduction

Groundnut (*Arachis hypogaea* L.) is a self-pollinated crop belongs to the botanical family Fabaceae of sub-family Papilionaceae, commonly known as the legume, bean, or pea family. Groundnut is rich in essential nutrients (USDA nutrient data,2020). In 100-gram groundnuts provide 2,385 kilojoules (570 kilocalories) of food energy and are an excellent source (defined as more than 20% of the Daily Value, DV) of several B vitamins, vitamin E, and several dietary minerals. They also contain about 25 g of protein per 100 g serving, a higher proportion than in many tree nuts.

In 2021, world production of groundnut (reported as peanuts in shells) was 49 MT. China had 16.6 million tonnes about 36% of global production, followed by India (14%). Other significant producers were Nigeria, Sudan and the United States. In India the total cultivated area under groundnut is 60.9 lakh ha, production is 10.21 MT with productivity of 1676 kg ha^{-1}. In Andhra Pradesh, it is cultivated in an area of 8.69 lakh ha, production is 7.74 MT with productivity of 894 kg ha^{-1}. (Directorate of Economics and Statistics, 2021).

Growing demand for food security has spiked the need of genetic improvement of crop germplasm. Genetic variability being a best option for crop cultivar improvement has intensively used in the past (Jaganathan *et al*., 2020).

Genetic parameters such as genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) are useful in detecting the amount of variability present in the genotypes. Heritability estimates along with genetic advance are more helpful in predicting the gain under selection than heritability estimates alone.

Material and Methods:

Thirty advanced breeding lines of groundnut were evaluated during *kharif*, 2021 in a Randomized Block Design (RBD), replicated thrice at Dry land farm, RARS, Tirupati. Each genotype was represented by three row plot of 5 m length with inter and intra-row spacing of 30 cm and 10 cm respectively. Standard crop husbandry practices and plant protection measures suggested for this crop were followed to raise a healthy crop. Data were recorded on five randomly selected competitive plants of each genotype replication^{-1} for 17 metric traits.

The pooled data were subjected to statistical analysis to test the homogeneity for error variance was applied by utilizing the Barlletts method (Panse and Sukhatme, 1961). Heritability (broad sense and narrow sense) was estimated by formula given by Allard (1960) and Lush (1940). Genetic advance as percent of mean can be classified according to proposed by Johnson *et al.*, (1955) as low (0-10%); moderate (10-20%) and high (20% and above). The phenotypic and genotypic coefficients of variation were computed by the following formulae given by Burton (1952). The data was analysed through software - Indostat 9.2 version.

RESULTS AND DISCUSSION:

The analysis of variance for 17 metric traits in 30 groundnut genotypes (Table 1) revealed existence of ample genetic variation in the material studied. Phenotypic and genotypic coefficients of variation, heritability in broad sense, genetic advance and genetic advance as per cent of mean for 17 characters involving 30 advanced breeding lines of groundnut are presented in Table 2. For all the characters studied, phenotypic coefficient of variation was found to be greater than genotypic coefficient of variation indicating the effect of environment on these traits. These results are in accordance with the findings of Narasimhulu *et al*. (2012), John *et al.* (2013), Kamdi *et al.* (2017), Mahesh *et al.* (2018), Nagaveni and Hasan Khan (2019), Rao *et al.* (2019), Kumari and Sashidharan (2020), Gali *et al.* (2021) and Bharath *et al.* (2022).

The characters, Pod yield plant^{-1} (GCV: 40.10 %; PCV: 41.23 %), Kernel yield plant^{-1} (GCV: 38.12 %; PCV: 39.68 %), dry haulms yield plant^{-1}(GCV: 37.81 %; PCV: 38.08 %) , number of mature pods plant^{-1} (GCV: 32.75 %; PCV: 33.47 %), number of primary branches plant^{-1} (GCV: 26.94 %; PCV: 28.04 %), harvest index (GCV: 21.93 %; PCV: 22.54 %) and plant height (GCV: 20.81 %; PCV: 20.92 %) exhibited high GCV and PCV. These results are in accordance with the findings of Hampannavar *et al*. (2018), Meghala *et al*. (2019), Venkataravana *et al.* (2020),Veer *et al.* (2021), Gali *et al*. (2021) and Mitra *et al.* (2021).

Moderate GCV and moderate PCV was exhibited by hundred pod weight (GCV: 17.31 %; PCV: 17.41 %) and hundred kernel weight (GCV: 13.67 %; PCV: 14.43 %) suggesting that individual trait selection can be resorted for improvement of these traits. The similar results are also observed in the findings of Roy *et al.* (2018) and Mitra *et al.* (2019).

High heritability was recorded for plant height (98.95 %), hundred pod weight (98.84 %), dry haulms yield plant^{-1} (98.61 %), oil content (97.87 %), protein content (97.65 %), number of mature pods plant^{-1} (95.78 %), harvest index (94.68 %), pod yield plant^{-1} (94.57 %), number of primary branches plant^{-1} (92.31 %), kernel yield plant^{-1} (92.29 %), hundred kernel weight (89.69 %) and shelling per cent (74.29 %) indicating that the effect of environment is least in expression of these characters. The results are in conformity with findings of Veer *et al*. (2021).

Higher genetic advance as per cent of mean was recorded for pod yield plant^{-1} (80.33 %), dry haulms yield plant^{-1} (77.35 %), kernel yield plant^{-1} (75.43 %), number of mature pods plant^{-1} (66.04 %), number of primary branches plant^{-1} (53.32 %), harvest index (43.97 %), plant height (42.65 %), hundred pod weight (35.46 %) and hundred kernel weight (26.67 %) indicating that these characters were governed by additive gene effect and the selection for these characters will be rewarding in crop improvement.

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High heritability coupled with high genetic advance as per cent of mean for pod yield plant^{-1}, plant height, number of mature pods plant^{-1}, shelling per cent, harvest index, number of primary branches plant^{-1} and kernel yield plant^{-1} were also reported by Narasimhulu *et al.* (2012), Rao *et al*. (2014), Gupta *et al.* (2015), Vasanthi *et al.* (2015), Choudhary *et al.* (2016), Chavadhari *et al*. (2017), Yusuf *et al*. (2017), Mahesh *et al.* (2018), Nagaveni and Hasan khan (2019), Gali *et al*. (2021), Shuro (2021) and Bharath *et al.* (2022),

Conclusion

The characters, Pod yield plant^{-1}, Kernel yield plant^{-1}, dry haulms yield plant^{-1} and number of mature pods plant^{-1} exhibited high GCV and PCV indicating ample amount of variation among the genotypes and the selection would be effective for further improvement of these characters.

High heritability coupled with high genetic advance as per cent of mean were recorded for characters *viz.,* plant height, hundred pod weight, dry haulms yield plant^{-1}, number of mature pods plant^{-1}, harvest index, pod yield plant^{-1}, number of primary branches plant^{-1}, kernel yield plant^{-1} and hundred kernel weight indicating preponderance of additive gene action in expression of these characters and selection would be effective for improvement of these characters.

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Table 1: Analysis of variance for physiological, yield attributes and quality traits in advanced breeding lines of groundnut

S. No	Characters	Replications	Genotypes	Error
		(df:2)	(df:29)	(df:58)
1	Days to 50 % flowering	2.033	4.031**	0.86
2	Days to maturity	1.88	4.132**	0.87
3	SPAD chlorophyll meter reading at 45 DAS	1.027	7.263**	1.783
4	Specific leaf area at 45 DAS (cm^2 g^{-1})	126.317	1166.803**	341.84
5	Relative water content (%)	35.901	85.278**	26.113
6	Harvest index (%)	5.047	306.989**	5.643
7	Plant height (cm)	5.616	516.552**	1.821
8	Number of primary branches plant^{-1}	0.525	10.726**	0.289
9	Number of mature pods plant^{-1}	2.593	58.560**	0.847

10	Hundred pod weight (g)	14.233	1486.055**	5.785
11	Hundred kernel weight (g)	8.611	124.691**	4.599
12	Shelling per cent	31.061	97.270**	10.061
13	Kernel yield plant^{-1} (g)	6.437	76.746**	2.08
14	Dry haulms yield plant^{-1} (g)	2.968	221.013**	1.034
** Significant at 1 % level				

Table 2: Estimates of genetic parameters for physiological, yield attributes and quality traits in advanced breeding lines of groundnut

S. No.	Character	Mean	Range		Variance		Coefficient of Variation		Heritability (Broad sense) (%)	Genetic advance (GA)	Genetic advance as percent of mean (%)
			Min.	Max.	Genotypic	Phenotypic	Genotypic	Phenotypic			
1	Days to 50 % flowering	27.03	24	29.33	1.05	1.91	3.8	5.12	55.1	1.57	5.81
2	Days to maturity	103.04	100	105.33	1.09	1.95	1.01	1.36	55.68	1.6	1.55
3	SPAD chlorophyll meter reading at 45 DAS	40.31	36	42.73	1.82	3.61	3.35	4.71	50.59	1.98	4.91
4	Specific leaf area at 45 DAS (cm^2 g^{-1})	169.93	140.43	237.9	274.98	616.83	9.75	14.61	44.58	22.8	13.42
5	Relative water content (%)	56.38	49.89	72.87	19.72	45.83	7.87	12	43.03	6	10.64
6	Harvest index (%)	45.68	26.06	65.69	100.44	106.09	21.93	22.54	94.68	20.08	43.97
7	Plant height (cm)	62.92	33.11	89.67	171.57	173.39	20.81	20.92	98.95	26.84	42.65

8	Number of primary branches plant^{-1}	6.92	5	12.4	3.47	3.76	26.94	28.04	92.31	3.69	53.32
9	Number of mature pods plant^{-1}	13.38	6.53	23.87	19.23	20.08	32.75	33.47	95.78	8.84	66.04
10	Hundred pod weight (g)	128.26	77.66	179.33	493.42	499.2	17.31	17.41	98.84	45.49	35.46
11	Hundred kernel weight (g)	46.27	33.33	61	40.03	44.63	13.67	14.43	89.69	12.34	26.67
12	Shelling per cent	68.38	52.44	79.78	29.06	39.13	7.88	9.14	74.29	9.57	13.99
13	Kernel yield plant^{-1} (g)	13.08	5.56	25.9	24.88	26.96	38.12	39.68	92.29	9.87	75.43
14	Dry haulms yield plant^{-1} (g)	22.64	12.4	45.47	73.32	74.36	37.81	38.08	98.61	17.51	77.35
15	Pod yield plant^{-1}(g)	19.33	7.73	35.77	60.11	63.56	40.1	41.23	94.57	15.53	80.33
16	Oil content (%)	49.44	45.62	53.39	3.55	3.63	3.81	3.85	97.87	3.84	7.77
17	Protein content (%)	25.31	21.28	28.48	3.5	3.59	7.4	7.48	97.65	3.81	15.06

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Medicinal Plants: The Future of Sustainable Healthcare

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Medicinal plants have played a vital role in human civilization and healthcare for centuries. This article explores the significance of medicinal plants from ancient traditions to modern healthcare systems. In the face of rising pharmaceutical pollution, lifestyle diseases, antibiotic resistance, and increasing healthcare costs, medicinal plants offer an affordable, eco-friendly, and sustainable alternative. They not only support human health but also contribute to the livelihoods of many tribal and rural communities who depend on them for income and traditional healing practices. The article also highlights the importance of conserving medicinal plant diversity and preserving indigenous knowledge. Integrating traditional wisdom with modern scientific approaches can create a path toward sustainable healthcare and self-sufficiency for future generations.

Introduction

From the ancient forests of Western Ghats to fertile Gangetic plains, India has been home to varieties of medicinal plants. Long before the use of contemporary synthetic drugs and medications, our ancestors have turned to the natural world for remedies, healing and cure. Remarkably this is still pertinent to modern day world. As the world struggles with antibiotic resistance, high healthcare cost, increase in chronic lifestyle diseases and loss of environment due to manufacturing of chemical drugs and their adverse reactions to our health, medicinal plants play a dynamic role in sustainable healthcare. In the recent era, the pharma industries have turned into a business market rather than service to mankind. The use of medicinal plants from the Vedic eras to the modern day have shown how self-sustainability has been in the lifestyle of human. This blog explores the use and significance of medicinal plants, their role in agriculture, healthcare and rural livelihood, scientific validation and how they are helping in shaping the path of self-sustainability for the future.

A Heritage Beyond Our Understanding

The historical use of medicinal crops dates back to 60,000-year-old Neanderthal burial. The first civilisations regarded medicinal plants as gifts from Gods, filled with magical power. Evidence of plant-based medicine has been found in 5000-year-old Sumerian clay slab. Likewise, Scripts about medicinal plants date back to almost 5000 years ago in India, China and Egypt, and at least 2500 years in Greece and Central Asia. Across the world, among all

the various traditional medical systems, Traditional Chinese Medicine (TCM) is currently the most popular, followed by Indian medicine. In Western countries, Oriental Medicine refers to Chinese, Japanese, and Korean medicines selected by immigrants from Korea, while "Asian medicine" often includes TCM, India (Ayurveda) and Tibetan medicine. Among all treatments in traditional medicine systems, medicinal plants are most frequently used. As civ ilisations developed, the

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significance of medicinal plants transformed from mystical to practical application. This leads to a scientific approach in cultivation and use of medicinal plants. Herbs trade connecting Europe, Asia, and Middle eastern countries between 300-600 BCE facilitated the exchange of knowledge and introduction of spices such as clove, from Moluccas to Egypt. For the Aztecs, cacao was not just food but also medicine. Mixed with herbs, it was used as a tonic to boost energy and treat heart ailments. Hibiscus infusion, popular in ancient Egypt, was used as a remedy for fever and to stay hydrated under the scorching desert sun. Peruvian natives observed that sick or feverish animals instinctively sought water from pools where cinchona trees grew which led to the discovery of Quinine, a crucial compound in treatment of Malaria. These early references to medicinal plants laid the groundwork for a herbal tradition that would evolve over millennia.

Potential Use And Significance Of Medicinal Plants

Tribal communities often possess the knowledge of medicinal plants, using them to treat various injuries and ailments. These indigenous knowledges passed down orally through generations, and specific individuals in their communities known as healers or herbalists. Since ancient periods, plant-based medicines played crucial role in healthcare. Even now, with modern pharmaceutical drugs, still 80% of the world relies on natural medicines. *Aloe vera* has been used by the Asians, Africans, Egyptians, Romans and the people of American continents. It is still the primary choice for treating burns, wounds, and ulcers. It possesses huge deal in cosmetic world, from ancient to modern era. *Aloe vera* is also taken orally for gynaecological problems. The value of folk knowledge can be illustrated with the example of *Phyllanthus amarus* (Keezhanelli), a plant used in Southern India for treating jaundice. The effectiveness of this plant in treating viral hepatitis-B was validated by an American Noble prize-winner who later patented this knowledge. Quinine extracted

from cinchona bark used to cure malarial fever traditionally in Peru. *Justicia adhatoda* or adathoda is indigenously used to treat ailments like cough, asthma, bronchitis, pneumonia, jaundice, leprosy, blood disorders, heart troubles, thirst, asthma, fever, vomiting, loss of memory, leucoderma, tumors, mouth troubles, sore-eye, fever, and gonorrhoea. The bark of *Alstonia boonei* contains alkaloids and histamine, which are useful in the treatment of fever, dizziness and high blood pressure. Ginger (*Zingiber officinale*) and Garlic (*Allium sativum*) are spicy additions to food that has long been used to maintain human health. Ashwagandha (*Withania somniferum)* can reduce stress, treats diabetes and hormonal imbalance thus reduces cortisol level in our body. It is not an exaggeration to say that medicinal plants have a great role to play in sustainable human health. The list can go on and on.

Pharmaceutical Pollution And The Real Remedy

Over 100,000 tonnes of pharmaceutical products are consumed globally every year. And where do you think their wastes go? Either they do get dumped in oceans affecting the marine ecosystems or poor countries get punished by these giants and completely swallowed by medical wastes. The wrong prescription or inappropriate use of drugs has adverse

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health problems. High dosage of use can be bigger toll on human health. Let's not start with high cost of medicines and potential rob of medical insurance. Countries like India escaped from these insurance problems as there are many free medical schemes from both union and state governments. But in the developed countries like the UK and the USA, people

go bankrupt because of their medical bills rather than get cured. This is right where our medicinal plants play a huge role. Along with horticultural therapy, plants can cure a person mentally, physically and emotionally. They are low cost, you can just grow them in your own backyard, and they can be a great addition to your diet. Consuming these plants on higher quantity will not have serious issues. They can be found everywhere just as the nature has given us, right under our nose. Pluck it, get a sniff, and just like that, half of your problems will vanish. If you get a bite, the other half will disappear. These are the gifts of mother nature, on which you don't have to spend a single penny and get completely treated if you're spend a single minute of your day.

Medicinal Plants In Rural And Tribal Economy And Their Preservation

For tribal and rural communities, medicinal plants are the primary source of income. But this potential can go destructively if left without conservation. Unsustainable utilisation of these plants can lead to severe loss of plant species and rip them off their ecosystems. Awareness about preservation of these native species is crucial for their conservation. One of the most effective strategies toward self-sustainability is the establishment of community-managed herbal gardens and nurseries. When local communities take ownership of cultivating medicinal species such as Ashwagandha, Brahmi, Neem, Tulsi, and Sarpagandha, they reduce pressure on wild plant populations while simultaneously creating a reliable, renewable source of income. Such initiatives also empower women and youth within tribal communities who traditionally hold knowledge of plant properties and usage.

SELF-SUSTAINABILITY FOR THE FUTURE:

Self-sustainability in medicinal plants refers to the ability of communities and ecosystems to meet their present needs without compromising the availability of these resources for future generations. For rural and tribal communities whose livelihoods depend heavily on harvesting of medicinal plants, building self-sustaining practices which is not merely an environmental choice, it is an economic necessity. Integrating traditional ecological knowledge (TEK)

and modern sustainable agriculture practices offers a powerful model. Indigenous people have long practised rotational harvesting collecting plants only in specific seasons and never exhausting a patch completely. Documenting and reviving such practices, supported by government policy and NGO partnerships, can ensure that medicinal plant populations regenerate naturally over time.

Conclusion

Medicinal plants offer a bridge between ancient wisdom and modern science, but their survival hinges on responsible stewardship. Conservation and ethical harvesting are not only ethical imperatives but also strategic steps to ensure a sustainable future for both humanity and the planet. By combining scientific knowledge, community engagement, and cultural sensitivity, we can pave the way for a world where medicinal plants thrive, ecosystems flourish, and generations to come benefit from nature's healing bounty.

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Plant tumor as Emerging Constraints on Agriculture Productivity and Food Security

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Plant tumors, also known as galls or abnormal growth, are a significant but often overlooked challenge to global crop productivity and food security. These unusual growths can be caused by various living agents, such as bacteria, Agrobacterium tumefaciens, viruses, fungi, nematodes, and insects, which hijack the plant's cellular processes to promote uncontrolled growth. When tumors form, they disturb normal plant functions by redirecting nutrients, blocking transport within the plant, and messing with hormone levels. This can lead to slower growth, lower yields, and poorer crop quality. For farmers, especially in parts of the world where resources are limited, plant tumors can cause serious post-harvest losses and make plants more vulnerable to other infections, further straining their finances. As climate change, large-scale farming practices, and international trade intensify, the spread and severity of these pathogens are worsening. This review explores how these tumors develop, their impact on crop productivity, and their implications for global food security. Gaining a better understanding of plant tumor biology is key to developing smarter disease-control methods, boosting crop resilience, and supporting sustainable farming to meet the growing global demand for food

1. Introduction

The most famous and widely studied plant tumor. It is caused by the bacterium *Agrobacterium tumefaciens*, a rod-shaped, Gram-negative soil bacterium widely known as "nature's genetic engineer," which inserts a piece of its own DNA (T-DNA) into the plant's genome. This forces the plant to produce excessive hormones (auxin and cytokinin) and an abnormal food source called opines. The modified plant cells are forced to produce opines, unique nitrogen-rich compounds that most other organisms cannot eat, but which *Agrobacterium* uses as its primary nutrient source (Figure 2).

Figure 2. Representative images of plant tumor (gall) formation observed in plants growing at Prof. Rajendra Singh (Rajju Bhaiya) University, Prayagraj, showing abnormal proliferative growth associated with pathogenic infection

1.1.How does it infect plants?

The infection process is a rare example of natural inter-kingdom genetic transfer, in which a bacterium integrates its DNA into a plant's genome. The bacteria sense chemical signals (like acetosyringone) released by wounded plant tissue and "swim" toward them using their tail-like flagella. The "Ti plasmid" that the bacteria carry is a specialized circular piece called a Tumor-Inducing plasmid. Once attached, the bacteria utilize the Ti (Tumor-Inducing) plasmid to inject specific genes into the plant. These newly integrated genes force the plant cells to overproduce growth hormones, such as auxin and cytokinin. This hormonal overdrive causes plant cells to divide rapidly and form tumors, which serve as a protective home and a food source for the bacteria. The *Agrobacterium* can survive in soil for several years (sometimes up to 2 years) even without a host plant nearby. In large trees, the bacteria can be found in soil layers as deep as 60cm. It spreads through contaminated soil, water movement, and unsterilized tools.

1.2.Losses and Impacts on Plants

Affected plants exhibit limited growth because the tumor functions as a nutrient and energy sink. Tumors hinder nutrient and water absorption, which can lead to increased production of fruit, nuts, and flowers. Woody tumors, knobby or knotted, may develop on stems, roots, or branches, sometimes reaching up to 30cm in diameter, causing the plant to become fragile and prone to breaking during pruning. Plants with tumors tend to be weaker, increasing their susceptibility to winter damage, drought, and other pathogens. Surface tumors often rot and die, leading to decay and a decline in the plant's aesthetic or market value.

1.3.Losses and Impacts on Agriculture

Tumors cause serious damage to nurseries, particularly affecting stone fruits, nuts, and ornamentals. Tumors on marketable parts (such as roots in root crops or stems in ornamentals) destroy the physical symmetry and appearance of the produce, rendering it unfit for sale. Losses of 10% to 30%, and in some cases up to 80%, have been reported in nurseries for pecan, walnut, and peach trees. In greenhouse cultures, such as roses, tumors can cause losses up to 60%. Infections require labor-intensive management, such as removing infected nursery stock, which increases labor costs and reduces profit margins. Localized infections can be managed by physically removing the tumor and affected tissue, sterilizing tools to prevent spread, and improving the plant's overall health to increase resistance.

2. Management of the Plant Tumor

a. **Pruning & Disposal:** Use sharp, sterilized pruning tools to cut away the galls. Be sure to cut several inches below the tumor into healthy tissue. Do not compost the infected material; burn it or dispose of it in the trash to prevent spore or bacteria spread.

b. **Sterilize Tools:** Disinfect your tools between every cut using a bleach solution (1 part bleach to 9 parts water) or rubbing alcohol so you don't transfer the bacteria to healthy plants.

c. **Soil Management:** If the tumor is on the roots (common in crown gall), the soil is likely contaminated. Remove the affected plant and do not plant susceptible species in that same spot for at least 2 to 3 years. You can solarize the soil by covering the patch with clear plastic during the hottest summer months to kill lingering pathogens.

d. **Preventing Wounding:** Many tumor-causing bacteria enter plants through open wounds. Protect your plants from lawnmower damage, deep pruning near the root crown, and root-feeding insects or nematodes.

e. **Isolate the Plant:** If the affected plant is in a pot, move it away from healthy plants immediately to prevent the bacteria (which can be spread by water splashes or tools) from spreading

Heat Treatment: For valuable seedlings, incubating dormant roots at 73F to 76F for 10 to 14 days before planting can help heal wounds, making them less susceptible to bacterial entry.

Conclusion

Plant tumors (often called galls) are benign, localized growths caused by pathogens, insects, or genetic anomalies. Unlike animal cancers, they do not metastasize (spread to other organs) because of rigid, immovable cell walls and the lack of a circulatory system, which allows the plant to typically live a normal lifespan.

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Redefining Water Security for the State through the State Water Policy

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This policy brief addresses the pressing challenges of water resource management in Madhya Pradesh, highlighting declining water availability, quality concerns, and rising sectoral demands. Using secondary data, it identifies trends in groundwater and surface water usage and contamination. Recommendations focus on integrated management, conservation, safeguarding water sources, enhancing efficiency, and promoting stakeholder participation. By fostering sustainability, innovation, and robust governance, the framework aims to ensure water security and resilience against climate change impacts while supporting socio-economic and ecological development.

Introduction

Water is a fundamental natural resource that is the basis of all natural and human activities. Water as a system is quite complex and cuts across the boundaries of physical, geographical, and social systems. Such complexity requires understanding and addressing challenges in the water sector holistically. Planning, development, and management of water resources must be governed by a common integrated perspective considering local, regional, and state contexts. It must also align with the objectives and agenda of the national water policy and international discourse on water governance and management, while transitioning towards a sustainable social, economic, and ecological development of human and natural systems. It needs to consider the various uses and users of water such as – domestic, agricultural, industrial and others.

Objective

The objective of this policy brief is to establish a rationale for revisiting the Madhya Pradesh State Water Policy (MP SWP), 2003, considering the developments in national and international discourses around climate change, water conservation and management.

Data and methods

The data used in this policy brief is taken from various secondary sources and published material of other researchers and organisations. These include the Central Ground Water Board, departments of the State Government of Madhya Pradesh, Census of India, etc. The data collected has been explored through basic data analysis approaches to identify evidence.

Status of water resources in MP

The Government of India considers any region with less than 1700 cubic metres per person annual water availability as water-stressed and less than 1000 cubic metres per person annual water availability as water-scarce[i] . Considering the demographic statistics and projections for Madhya Pradesh by the Census[ii] and Ministry of Health and Family Welfare,[iii] respectively, since a little ahead of 2011, MP has been water-stressed as the annual per capita availability of water is 1611 cubic metres in 2011[xiv]. Considering constant annual water availability, this is projected to fall up to 1244 cubic metres per capita by 2031. If the trend continues, this could lead to the state becoming water-scarce by 2040.

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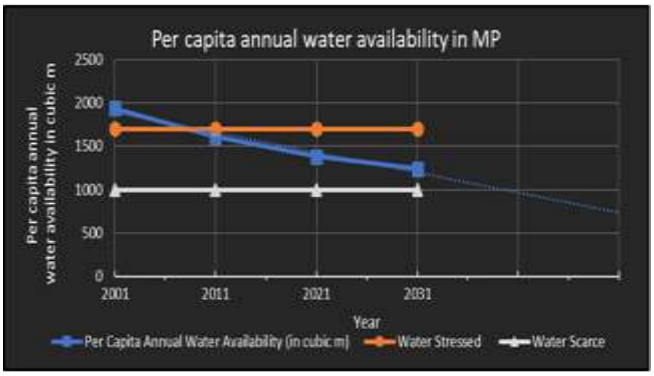

Figure 1 Current and Projected per capita annual water availability in Madhya Pradesh 2001-2051

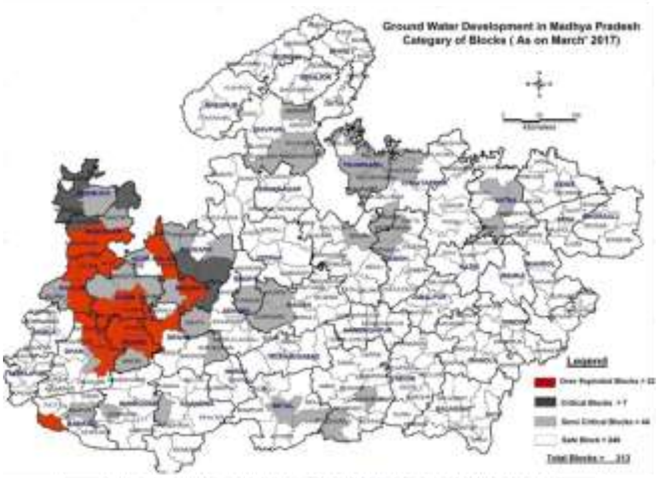

Figure 2 Groundwater Development in Madhya Pradesh (district-wise)

The net annual groundwater available in the state is 34.47 billion cubic metres (BCM),[iv] while the annual surface water availability is 81.5 BCM[v]. This makes up a total of 117.03 BCM as the total annual water available in the state.

Out of the 34.47 BCM of groundwater available annually in the state, 18.88 BCM is the gross withdrawal of groundwater[vi]. This makes the stage of groundwater development in Madhya Pradesh 54.76%. 240 blocks are categorised as Safe in terms of the stage of groundwater development. There are 22 over-exploited, 7 critical and 44 semi-critical blocks in MP (**Error! Reference source not found.**)[vii]. While the number of over-exploited blocks has reduced in comparison to 2007 by 2, the total number of blocks at the critical stage increased from 5 to 7, and the semi-critical blocks increased significantly from 17 to 44 (Figure 3).

Central Ground Water Board data shows that about 19 districts in MP are having fluoride contamination in groundwater[viii]. Alarmingly, almost all districts have nitrate and iron contamination in the groundwater[ix]. At the same time, major growth centres of MP have high heavy metal contamination reported in the groundwater[x].

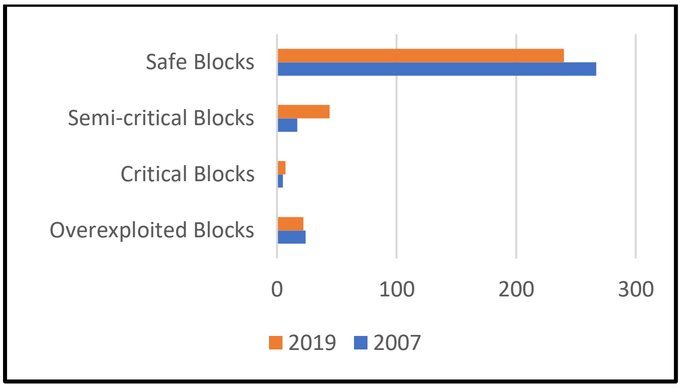

Figure 3 Number of blocks under various stages of groundwater development 2007-2019

Sectoral water usage in MP

Out of the total groundwater withdrawal, 92.32% is used for irrigation, 6.57% is used for domestic water supply while is rest is used for industrial purposes[xi]. Whereas the surface water in MP is used mostly to fulfil domestic and agricultural demand. Data is scarce on the use of water in agriculture and industries, however, some past data shows that the use of ground water sources for irrigation is higher compared to surface water (Figure 4)[xiii].

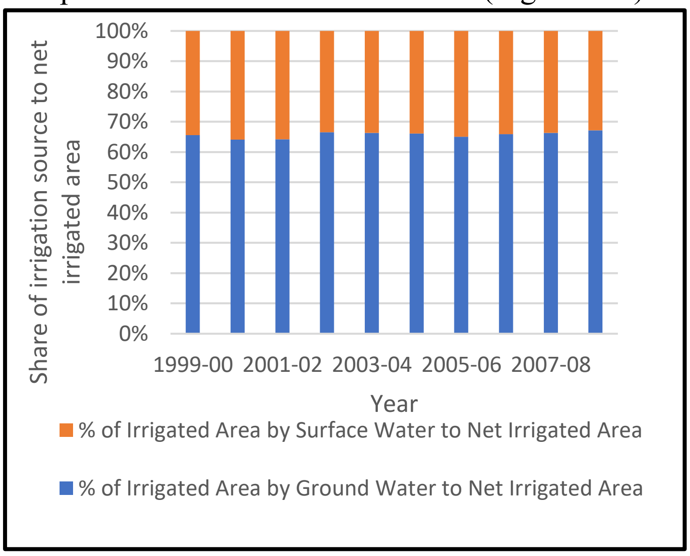

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Figure 4 Share of the source of water to the net irrigated area in Madhya Pradesh

Approximately 1.2 BCM annually is the domestic water demand of the population of MP.

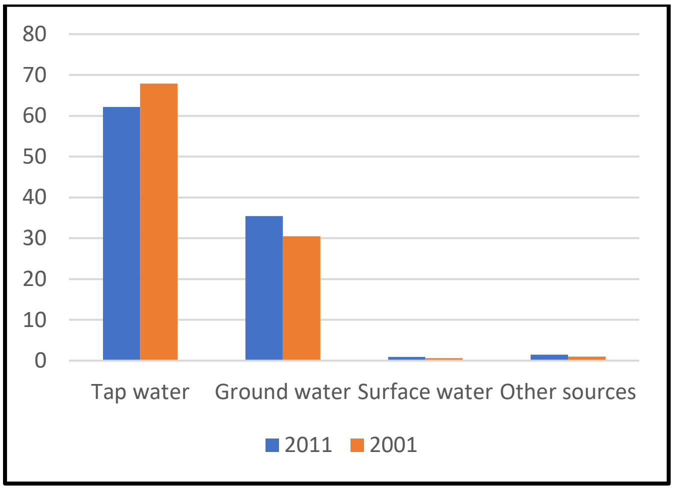

Figure 5 Share of water sources in urban MP

The urban population is highly dependent on the ground water, and there is an increasing trend in the share of groundwater as a source to fulfil domestic water demand (Figure)[xiii].

Shifting Metrics in Rural Water Security: From Habitations to Household Taps

Between 2021 and 2022, Madhya Pradesh assessed rural water coverage using the State-Specific Parameters and Criteria (SSPC), which defined full coverage as 55 litres per capita per day (lpcd) across ~127,000 habitats, including tolas, majras, and paras. Around 80,000 habitats met the norm, while 47,500 were partially covered.

From 2023, with the rollout of the Jal Jeevan Mission (JJM), the state adopted a more stringent norm—100% Functional Household Tap Connections (FHTCs)—and shifted reporting to 51,415 revenue villages only. Under this, just 7,389 villages were fully covered, not due to regression but due to the more granular and household-focused criterion.

Despite this transition, infrastructure strengthening continued, with handpump replacements rising steadily from ~559,000 in 2021 to over 564,000 in 2023, indicating a parallel approach—advancing piped water systems while sustaining traditional sources[xv].

Challenges to water resource management since MP SWP 2003

The current water policy of Madhya Pradesh, the State Water Policy (MPSWP) 2003, was aligned with the National Water Policy of India, 2002. Since then, the country has witnessed major changes that have stressed the water sources indiscriminately. The National Water Policy of India, 2012, was notified to ensure that climate change-induced stresses, along with the impacts of anthropogenic activities on the water, are actively addressed and prevented; however, MP does not have any such provisions. MP receives all its water from three major sources- rain, groundwater, and surface water bodies such as seasonal rivers and lakes. The rivers include major rivers such as Narmada, Betwa, Son, Tapi, Chambal, etc. The quality of water in Madhya Pradesh is well recognised for its pristine quality and therapeutic properties. Since the availability of water is limited, all users and activities must get sufficient water while simultaneously ensuring the resilience of the water resource

system towards climate change-induced impacts. The state water policy is a step towards ensuring that, while maintaining environmental sustainability, Madhya Pradesh contributes towards the aim of India of becoming a 5 trillion economy. Along with ensuring that water use is sustainable in the existing activities, it must also promote water-based industries and activities.

Jal Samvardhan Abhiyan: A Strategic State Initiative

The Jal-Ganga Samvardhan Abhiyan (JGSA) under MGNREGA is Madhya Pradesh's flagship water conservation programme aimed at strengthening groundwater recharge, improving farm-level water security, and enhancing climate resilience through farm ponds, dugwell recharge structures, and Amrit

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Sarovar works. Under the campaign, Madhya Pradesh is showing notable progress across all key interventions, supported by strong field-level momentum, effective coordination, and robust administrative push.

So far, 3,530 farm ponds (4.1%) and 2,540 dugwell recharge structures (2.4%) have been completed, while over 86,000 farm ponds and 1.05 lakh dugwell recharge works have been initiated, indicating strong groundwork. The Amrit Sarovar initiative is also moving forward, with 1 completion and 529 works ongoing out of 530 sanctioned. The steady advancement across interventions reflects well-established execution systems, active community mobilisation, and efficient fund utilisation.

Financial performance remains robust, with ₹1,022.16 crore booked out of ₹2,120.74 crore for farm ponds and ₹196.15 crore booked out of ₹267.90 crore for dugwell recharge, indicating effective utilisation and smooth fund flow. With resource flow aligned to ground execution and a large volume of works underway, the state is building a solid foundation for long-term water conservation outcomes.

Daily progress trends over the past 14 days indicate steady improvement, with farm pond completions increasing from 3,460 to 3,762 and dugwell recharge structures rising from 2,504 to 2,716. With this sustained momentum, the Jal-Ganga Samvardhan Abhiyan is well-positioned to achieve significant improvements in groundwater recharge, promote sustainable water use, and enhance climate resilience across the state[xvi] .

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ISSN: 3049-2289

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AGRICULTURE BULLETIN

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The Crisis of Paddy Cultivation in Eastern Uttar Pradesh During a Fuel Shortage

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Eastern Uttar Pradesh (Purvanchal) remains highly dependent on paddy cultivation as its primary monsoon crop, anchoring the region's food security and rural economy. However, structural deficits in public canal infrastructure have forced an overwhelming reliance on diesel-powered groundwater tubewells for irrigation. This article examines the compounding vulnerabilities faced by smallholder farmers in this region during acute fuel shortages and price spikes. By analyzing input-output dynamics, irrigation costs, and subsequent yield penalties, we demonstrate how high fuel costs disrupt critical transplanting timelines, compress profit margins to negative thresholds, and jeopardize regional food security. The paper concludes with policy recommendations for solarization, grid-electricity extension, and canal revitalization to mitigate future macroeconomic shocks.

Paddy cultivation (*Oryza sativa*) during the Kharif season is the economic backbone of Eastern Uttar Pradesh, a region characterized by high population density, small landholdings, and a high concentration of marginal farmers. Paddy is a highly water-intensive crop, requiring approximately 1,200 to 1,500 millimeters of water throughout its vegetative and reproductive cycles. Historically, the region relied on the South-West monsoon to meet the bulk of this requirement. However, shifting precipitation patterns, characterized by delayed monsoonal onset and frequent dry spells, have made supplementary irrigation absolutely mandatory for survival of the crop.

Unlike Western Uttar Pradesh, which benefits from an extensive network of state-managed canals and a highly subsidized, reliable agricultural electricity grid, Eastern Uttar Pradesh features a highly fragmented, diesel-dominated irrigation landscape. It is estimated that over 70% of the irrigated area in Purvanchal relies on private or rented diesel pump sets extracting groundwater. Consequently, any shock to the supply chain or price of petroleum products triggers an immediate, systemic crisis in the agricultural sector of the region.

The Mechanics of Vulnerability: Diesel Dependency

The structural vulnerability of paddy cultivation in Eastern Uttar Pradesh can be mathematically framed through the direct relationship between irrigation cost and fuel price. When surface water infrastructure is absent, the total cost of production per hectare (C_{total}) becomes highly sensitive to the cost of running diesel engines (C_{fuel}).

$$C_{total} = C_{seeds} + C_{fertilizer} + C_{labor} + [\,(P_{diesel} \times R_{consumption}) \times H_{irrigation}\,]$$

Where P_{diesel} represents the price of diesel per liter, $R_{consumption}$ is the rate of fuel consumption of the pump set (typically 1.0 to 1.5 liters per hour for standard 5-horsepower engines), and $H_{irrigation}$ is the total number of hours the pump must run across the season. During a fuel crisis, P_{diesel} increases exponentially due to direct supply scarcity and

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black-marketing, driving up the variable cost component to unsustainable levels.

Furthermore, small and marginal farmers who do not own pump sets must rent irrigation services from wealthier landowners. During fuel shortages, rental rates escalate not just linearly with fuel costs, but include a scarcity premium, further penalizing resource-poor farmers

Impact on Critical Agronomic Timelines

Paddy cultivation operates under rigid biological timelines. The delay of even a few weeks in key operations can drastically reduce final crop yields. A fuel crisis impacts these timelines in two critical phases:

1. **Nursery Development and Transplanting Delays**

   Paddy seeds are first sown in nurseries and transplanted into puddled fields after 21 to 25 days. Puddling requires heavy watering to create an impermeable clay layer that retains standing water. If diesel is unavailable or unaffordable during June and early July, farmers delay transplanting while waiting for rainfall. When seedlings remain in the nursery past 35 days, they age excessively, leading to poor tillering, reduced panicle length, and ultimately, lower grain yields.

2. **Mid-Season Dry Spells and Moisture Stress**

   The reproductive phase (panicle initiation to flowering) is the most critical moisture-sensitive period for paddy. Drought stress at this stage causes high spikelet sterility and unfilled grains. During a fuel crisis, farmers are forced to ration water, providing insufficient irrigation or abandoning fields entirely, leading to catastrophic crop failures.

Table 1: Comparative Mechanics of Cultivation Costs and Yield Trajectories under Fuel Scarcity

Cultivation Parameter	Standard Operating Scenario	Fuel Crisis / Shortage Scenario	Net Impact / Margin Loss
Avg. Irrigation Cost / Hour	INR 150 – 180	INR 280 – 350 (including premium)	Increase of 85% to 100%
Total Irrigation Shifts Required	12 – 15 waterings per season	6 – 8 waterings (forced rationing)	Severe moisture stress incurred
Transplanting Timeline	Optimal (Mid-June to early July)	Delayed (Late July to early August)	Seedling over-aging (35+ days)
Average Yield (per Hectare)	4.2 – 4.8 Metric Tons	2.8 – 3.2 Metric Tons	30% to 35% decline in output
Net Profit Margin	Positive (Subdued but stable)	Negative (Debt entrapment)	Loss of livelihood capital

Socio-Economic Ramifications

The cascading effects of a fuel-induced paddy crisis extend far beyond immediate crop loss, reshaping the socio-economic fabric of Eastern Uttar Pradesh:

- **Escalating Rural Indebtedness:** To secure fuel at black-market rates, marginal farmers borrow capital from informal village moneylenders at exorbitant interest rates (frequently 36% to 60% per annum).

ISSN: 3049-2289

A subsequent suppressed yield ensures an inability to repay, triggering a cycle of structural debt entrapment.

- **Forced Out-Migration:** When localized farming becomes economically unviable due to high input shocks, agricultural laborers and smallholders migrate prematurely to urban centers like Delhi, Mumbai, and Surat in search of manual wage labor.
- **Regional Food Insecurity:** Paddy in Purvanchal is grown primarily for self-consumption. A drop in household production reduces grain storage for families, forcing them to buy expensive grain from open markets, resulting in dietary compromises and malnutrition among women and children.

Policy Interventions and Path Forward

To decouple the food security of Eastern Uttar Pradesh from volatile fossil fuel supply chains, comprehensive structural reforms are urgently required:

1. **Accelerated Solarization (PM-KUSUM Scheme):** The transition from diesel engine pump sets to solar-powered submersible pumps must be fast-tracked with higher subsidy allocations targeting marginal farmers. Solar energy offers a zero-marginal-cost irrigation alternative once installed.
2. **Electrification of Agricultural Feeders:** State electricity distribution companies (DISCOMs) must prioritize dedicated agricultural power feeders throughout Purvanchal, guaranteeing 8 hours of uninterrupted, subsidized grid power during the Kharif season.
3. **Rejuvenation of Local Surface Water Bodies:** Mass public works under MGNREGS should focus on desilting traditional ponds (*pokharas*), community tanks, and vintage canal distributaries to maximize rainwater harvesting and reduce reliance on groundwater extraction.

Conclusion

The crisis of paddy cultivation in Eastern Uttar Pradesh during a fuel shortage underscores the extreme vulnerability of a food production system tied to fossil fuels. In an era of climate volatility, ensuring regional stability demands an immediate transition away from diesel irrigation. By investing heavily in solar-powered pumps, expanding grid electrification, and restoring local water infrastructure, policy makers can build a resilient agricultural ecosystem that insulates marginal farmers from global energy shocks and protects the breadbasket of Uttar Pradesh.

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BioLPG: A Sustainable Solution to Energy Challenges and Its Prospects in India

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1. Introduction: Energy crisis and need for alternative solutions

The energy security transition across the globe is getting redefined under the testing situations transforming rapidly with unknown possibilities raised from geopolitical tensions, longing wars, climate change, tariff impositions and hindering supply chains. Among these situations, India, being taken into account as one of the major importers of energy and most populated country of world facing a significant challenge to fulfill rising demands and catering development activities with focus on system resilience, domestic self-reliance (***Atmanirbhar Bharat***) and climate change mitigation.

Due to current situation households are facing challenges to cater LPG needs in Urban, Semi-urban and rural areas. Although the schemes like ***Ujjawala Yojana*** have expanded LPG system access; affordability and refilling along with continuous supply is a concern needs to be tackled. In this context, while going through alternatives, Bio-LPG i.e. Bio-propane emerges as a promising renewable energy alternative. This option can be used to strengthen energy security with mitigation of climate change. Bio-LPG is a fuel derived from diverse biomass feedstocks such as agricultural residues and waste products providing carbon neutral alternatives to LPG. This is low carbon intensive option reducing GHG emissions significantly. This characteristic of Bio-LPG as a renewable fuel is pivotal component for achieving decarbonization targets set by India. The utilization of Bio-LPG is advantageous as it addresses energy demand and restrict air pollution caused due to stubble burning. This pathway needs to be assessed for sustainable Indian energy transition. Majority of Indian sectors are reliant on biomass energy and rural people still rely on biomass as major cooking fuel. The strategic integration of Bio-LPG is needed for sustainable development and energy self-sufficiency and self-reliance.

2. What is BioLPG?

The Bio-LPG is defined to be a renewable energy based liquefied petroleum gas generated from processing of agricultural residues, leftover biomass and organic waste materials. This process often involves various bio-energy conversion processes like hydrotreatment, gasification followed with synthesis and separation providing a chemically identical form to LPG. This Bio-LPG is compatible to support through existing LPG infrastructure making it convenient for utility and without adding any economical burdens. This seems to be most prior approach as it contributes to a circular economy through valorizing waste materials reducing overall waste generation and providing a sustainable energy source. The chemical equivalence allows seamless integration with current supply chains and end-user applications. This direct compatibility significantly lowers the barriers in adoption. This transformation can transit away from fossil fuels in sectors including commercial, domestic and industrial sectors. Being environmentally significant it is suitable alternative to conventional LPG. Bio-LPG can be obtained from diverse biomass feedstocks contributing waste valorization and circular economy principles. Key Characteristics of Bio-LPG are as shown below.

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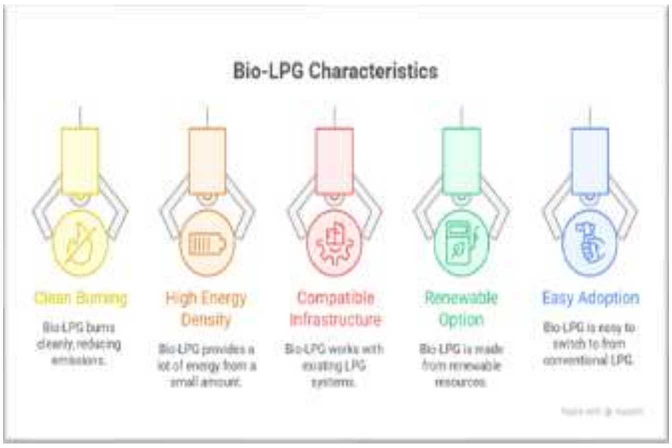

Fig. 1 Bio-LPG characteristics

3. Importance of Bio-LPG in the Current Energy Scenario

The evolving energy landscape of India is characterized by escalating demand, heavy reliance on imported fossil fuels and pressing environmental imperatives. The major transformative solution is Bio-LPG which addresses multiple facets of energy trilemma viz. *Security, Sustainability and Accessibility*. This adheres with target of 50% renewable energy power production by 2030 and net zero emissions by 2070. By leveraging available domestic biomass resources; bioenergy-based Bio-LPG production not only mitigates vulnerabilities of import burdens but also reduces GHG emission. This is helpful for promotion of rural energy equity providing cornerstone for sustainable development.

3.1 Energy Security

India's LPG dependence with more than 60% imports is well known and is exposed to geopolitical risks, supply disruptions, volatile market prices. This has been major concern for energy security and rising domestic and domestic demands. Bio-LPG counters this by harnessing locally available biomass resources; thereby fostering self-reliance and reducing imports. The decentralized production at community and regional level can minimize embodied transportation costs and can enhance supply chain resilience. This shift to renewable fuel like Bio-LPG diminishes impact of global energy markets strengthening national energy sovereignty. Furthermore, by valorizing domestic bio-waste it stimulates rural economics through employment generation in process scenarios like collection, processing, distribution and utilization etc.

3.2 Environmental Benefits

Usage of Bio-LPG provides sustainable environmental advantages as it reduces GHG emission by 70-90% compared to fossil LPG due to its carbon neutral biomass origins and low carbon intensity. This reduction provides a closed pathway and runs circular ecology as biogenic CO_2 is circulated throughout lifecycle. This is useful for India's commitment towards Paris agreement. Furthermore, Bio-LPG combustion reduces particulate matter emissions addressing issues for indoor air pollution in comparison to traditional biomass burning. Bio-LPG production paradigm advances circular economy principles by diverting organic waste from landfills curbing methane emissions and providing valuable byproducts.

3.3 Enhancing Rural Energy Access

Indian rural economy met its energy demand from biomass-based sources where Bio-LPG can emerge as an ideal clean cooking alternative for underserved households. It can utilize existing LPG infrastructure including 340 million domestic LPG users. This "drop in" compatibility ensures immediate scalability, affordability and user familiarity bridging the clean energy access gap for semi-urban and remote areas where electricity is not consistent. By excluding use of polluting fuels like Dung-cakes and crop residues; Bio-LPG not only enhance fuel security but also minimizes drudgery faced by women and children with conservation of forests and enhancing agricultural productivity. Policymakers can take note of advantages of Bio-LPG and can amplify this through subsidy or incentive based schemes for adoption and utilization aligning with SDG 7 for universal clean energy.

ISSN: 3049-2289

4. Production Processes of Bio-LPG

Bio-LPG is renewable energy-based fuel equivalent to conventional LPG and is primarily generated through a thermochemical, biochemical and synthetic pathways. Often as a valuable co-product alongside other biofuels. The agricultural residues, organic waste, used cooking oils can primarily be used for generating bio-LPG. While bio-diesel and ethanol production are more matured and has upscaled unlike gasification and other techniques for large scale deployment particularly in residue rich region. The following subsection describe the key production processes highlighting their mechanism, production capacity and suitability for Indian context.

4.1 Biodiesel Production

The biodiesel production is most matured and commercially used bioenergy conversion technique and widely be used for Bio-LPG. For producing Bio-LPG under this method vegetable oils, animal fats, or even used cooking oil are converted into biodiesel using process of transesterification. During this process, triglycerides react with methanol (in the presence of a catalyst) to form biodiesel and a by-product as crude glycerol is obtained. This byproduct glycerol is further refined and processed to produce propane and butane i.e. Bio-LPG. Generally, from process of production of 1 ton of Bio-diesel provides 50 kg Bio-LPG. The process is very efficient, with yields of up to 95%.

4.2 Hydrotreated Vegetable Oil (HVO) route

This method works especially well in India because there are so many sources of used cooking oil and non-edible oils like jatropha. It helps the circular economy by turning waste into useful energy. Since India is already promoting biodiesel blending under its National Biofuel Policy, this method can easily fit in with existing systems, making energy security better and reducing the need for imports. Commercial plants in Europe have already shown that this technology is ready for large-scale use in India. It involves hydrogenation of oils and fats under high pressure to produce renewable diesel as the main product. During this process, the glycerol is converted into propane and further into Bio-LPG (about 30–70 kg/tonne feedstock). In this process apart from Bio-LPG, small amounts of water, CO_2/CO, light hydrocarbon gases, and bio-naphtha are also produced. Bio-LPG synthesized from the process is of high purity, so it doesn't need extra processing. This makes HVO process as cost-effective and scalable to make bio-LPG.

4.3 Gasification coupled with Fischer–Tropsch Synthesis

Gasification coupled with F-T synthesis is one of the promising ways to make Bio-LPG. The gasification is carried out at very high temperatures (800–1000°C) in limited supply of oxygen and can accommodate agricultural residues such as rice husk, sugarcane bagasse, and wheat straw into producer gas or syngas consisting mainly of carbon monoxide, hydrogen, carbon dioxide, and methane. The syngas produced is cleaned and processed using Fischer–Tropsch synthesis where gaseous fuel is converted into liquid fuels and lighter hydrocarbons like propane and butane. Bio-LPG accounts for about 10–20% of the total liquid products. This method is especially good for commercial purposes and is suitable for India, which produces about 228 million tons of agricultural residues which are prone to stubble burning. Using these leftovers can greatly cut down on stubble burning and the air pollution caused. The initial investment is processing is high, but system CHP (Combined Heat and Power) can make it work better overall, making it a good choice for future bio-refineries under programs like SATAT.

4.4 Biogas Upgrading and Liquefaction

In rural India, biogas (*Gobar Gas*) production is a common way to make energy using cattle waste. It uses anaerobic digestion to break down organic waste like animal dung, food waste and municipal waste. Biogas is mainly composed of methane and carbon

ISSN: 3049-2289

dioxide. To make Bio-LPG, this biogas is refined to get rid of impurities like hydrogen sulfide and moisture. This is carried out by using methods like pressure swing adsorption or membrane separation. The purified gas is then put through catalytic reactions to make propane and butane. These gases are further compressed to liquid under moderate pressure to make Bio-LPG. This method is great for decentralized and community-level uses. It not only makes clean cooking fuel, but it also makes digested slurry or spent slurry, which can be used as a biofertilizer. It also helps lower methane emissions from waste, which helps to mitigate climate change. This method cuts greenhouse gas emissions by up to 90%, making it a great choice for long-term rural energy systems.

4.5 Pyrolysis of Biomass

Pyrolysis is another thermochemical conversion technology that heats biomass without oxygen at temperatures between 400 and 600°C. This process breaks down biomass into bio-oil, gases, biochar, and small amounts of Bio-LPG. The gaseous part contains propane and butane, which can be separated and condensed to make Bio-LPG. Pyrolysis has a low yield (around 5–10%), but it can use a wide range of feedstocks, such as agricultural waste and municipal solid waste. It also makes useful byproducts like bio-oil (which is used in chemicals and fuels) and biochar (which is used to improve soil). Bio-oil is acidic, so it needs to be improved even more to make the fuel better. People are still working on this technology, but it has a lot of potential for the future.

4.6 Power-to-X Pathways

Power-to-X (PtX) technologies are a new and advanced way to make Bio-LPG. In this method, renewable electricity (from solar or wind) is used to make hydrogen through electrolysis. This hydrogen is then mixed with carbon dioxide that has been captured to make fuels like methanol, which can be turned into LPG-range hydrocarbons. This method is especially appealing because it can produce almost no carbon emissions when powered by renewable energy. It also works well with India's growing renewable energy capacity and can use CO_2 from industrial or biogas sources. Although it is still in the early stages of development and is currently expensive, ongoing advancements in technology and decreasing costs of electrolyzer are expected to make it more feasible. Additionally, new ideas like co-processing biomass and plastic waste are being looked into to improve fuel yields and solve environmental problems at the same time.

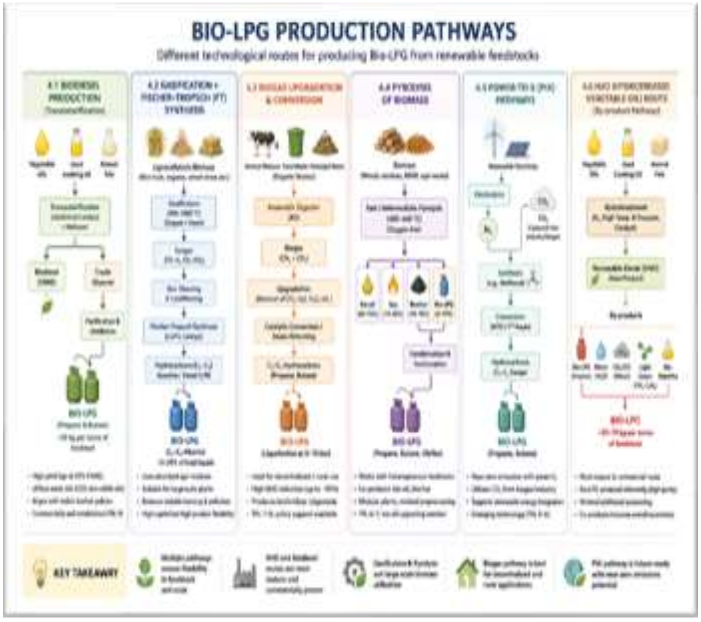

Fig. 2. Bio-LPG production pathways

5. Applications of Bio-LPG

Bio-LPG as a renewable fuel chemically similar to conventional LPG has multiple applications across domestic, industrial, agricultural, transportation, and energy backup sectors as India has one of the most extensive LPG infrastructure for seamless integration.

5.1 Domestic Cooking Fuel

In rural, semi-urban and urban households Bio-LPG can be used as fuel alternative to LPG which can mitigate indoor air pollution from traditional biomass fuels like firewood and dung.

ISSN: 3049-2289

5.2 Industrial Heating

Industries are reliant on LPG for process heating such as food processing, textiles, tiling and ceramics. Bio-LPG plants can provide a powerplant model that can provide energy at industry level with lower carbon intensity and supporting decarbonization pathways. Its compatibility ensures no modifications to burners or equipment, facilitating immediate uptake in India's manufacturing hubs.

5.3 Agricultural Operations

Bio-LPG can be used for feed cooking, drying, electricity generation, lighting, irrigation pumps and greenhouse heating in agriculture thus valorizing on-farm residues while enhancing efficiency in residue-rich regions

5.4 Transport Fuel

As transport fuel Bio-LPG based vehicles can offer higher octane and lower emissions than gasoline, suitable for three-wheelers and buses in urban fleets.

5.5 Backup Fuel in Hybrid Renewable Systems

Bio-LPG provides reliable storage and dispatchability in solar-wind hybrids, addressing intermittency and enabling grid stability in decentralized setups like those under SATAT.

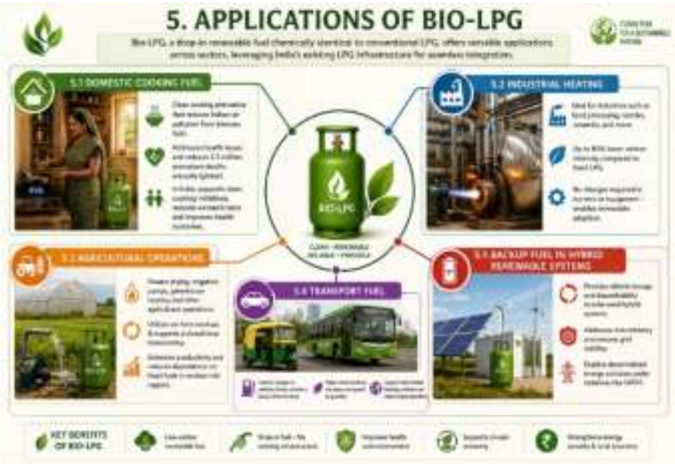

Fig. 3. Applications of Bio-LPG

6. Prospects of Bio-LPG in India

India's Bio-LPG trajectory is promising and has abundant feedstocks, robust infrastructure, supportive policies, and substantial market demand, positioning it as a key enabler for energy security and net-zero goals by 2070.

6.1 Strong Feedstock Availability

India generates vast biowaste resources from agricultural residues (rice husk, bagasse, straw), animal manure from cattle, used cooking oil from households and hospitality, and municipal solid waste. These feedstocks sustain multiple production pathways from hydrotreatment to gasification thus fostering waste-to-wealth models and averting open burning or landfilling.

6.2 Existing LPG Infrastructure

Due to similarity of chemical composition and scope for blending or without blending Bio-LPG can be used with same infrastructure as of LPG.

6.3 Government Initiatives

Government initiatives like SATAT promote compressed biogas which are extensible to Bio-LPG. Emerging blending mandates and incentives could bridge policy gaps, spurring investments.

6.4 Market Potential

As the world's third-largest LPG consumer with high import reliance, India faces surging rural demand from population growth. Bio-LPG could minimize imports, cut GHG emissions and fulfill ambitions of Atmanirbhar Bharat.

7. Challenges in Adoption

Despite the promising prospects of Bio-LPG, several barriers hinder its widespread adoption in India due to lack of spanning policy, technological, economic and infrastructural utilities.

7.1 Policy and Regulatory Gaps

India lacks a dedicated Bio-LPG blending mandate or policy framework akin to those for ethanol and biodiesel, where blending targets stand at 9.3% and 0.07%, respectively, yet remain unmet due to feedstock and implementation challenges.

ISSN: 3049-2289

Furthermore, the absence of assured pricing mechanisms discourages investor confidence, as fluctuating fossil LPG prices and inadequate incentives fail to bridge the cost gap, contrasting with supportive schemes like SATAT for compressed biogas.

7.2 Production Scale-Up

Current Bio-LPG production remains nascent and limited. It is constrained by insufficient large-scale facilities and reliance on pilot or demonstration plants. Scaling up requires substantial capital investment in advanced technologies such as hydrotreatment and gasification.

7.3 Cost Competitiveness

Bio-LPG incurs higher upfront production costs compared to fossil LPG due to feedstock processing, energy-intensive conversion and low economies of scale making it uncompetitive without external support. Subsidies, carbon pricing, or fiscal incentives are essential to offset these premiums.

Fig. 4. Bio-LPG prospects and challenges

7.4 Technology Maturity

Many Bio-LPG pathways are at TRL 5–6 which mandates strict R&D to achieve commercial reliability and optimize yields from diverse feedstocks. This immaturity is exposing risks for early adopters in hard-to-abate sectors.

8. Future Outlook

The global Bio-LPG market is poised for rapid expansion. Compared to European excel in same field India has to initiate the task. India being the third-largest LPG consumer with surging rural demand amid population growth and import dependence, Bio-LPG emerges as a pivotal player, capitalizing on abundant biomass, existing connections and policies like the National Biofuels Policy. These policies can have targeted interventions like blending mandates, incentives, and technology scaling for uplifting Bio-LPG usage thereby reducing fossil imports and fortify energy security under Atmanirbhar Bharat. However, the economic sustainability is the key to be addressed in near future.

9. Conclusion

Bio-LPG represents a strategic biofuel for India with an opportunity to use surplus biomass residues and mitigate GHG emissions with prior energy security. Overcoming challenges in policy gaps, production scale-up, cost competitiveness and maturity of technology with prior field level adoption requires a comprehensive framework with dedicated blending mandates, assured pricing mechanisms, fiscal incentives, collaborative R&D and investments in feedstock aggregation and decentralized production. Bio-LPG needs government support, technological innovation and private investment for better commercialization, boost the evolution from niche to mainstream for fortifying Atmanirbhar Bharat goals on sustainable fuels and energy security.

AGRICULTURE BULLETIN
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Fuelwood consumption and trade in India

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Introduction

Firewood has been a major source of energy for ages and is still a primary source of energy in most of the rural households worldwide. India is one of the world's largest consumers of fuelwood. India annually consumes an additional 270 million tons of fuelwood, 2800 million tons of fodder and about 102 million cubic meter of forest products – valued at about Rs 27,500 crore a year. India's consumption of fuelwood is about five times higher than what can be sustainably removed from forests. In India, 49% of homes utilize fuelwood as their main source of energy for cooking (Khanwilkar et al. 2021). Around 80 per cent of rural people and 48 per cent of urban people use fuelwood. Despite good economic linkages, flexibility (for capital, technology, etc) and diversity of forest resources, forest-based timber processing industries are generally handicapped due to inefficient operations, legal restrictions, low output, non-availability of skilled labour and resultant inertia. In terms of wood (and increasingly bamboo) utilisation in India, there are some 23,000 sawmills of varying capacities (mostly small and unsophisticated technically). Of these, 950 units manufacture wood-based panel products and veneer sheets; 380 units produce pulp, paper, and paperboard; 5 units produce safety matches (with an unknown number of cottage-scale units); plus, many units are involved in downstream processing and recovery, and further processing of residues. 70 to 90 per cent of the plants are in small-scale sectors. Most production units are short of investment capital, hire unorganised and legally unprotected labour, use outdated machinery, and are characterised by poor management and technical skills. In sawmills, for example, only 3% of products generated meet Indian grading standards. Processing technologies in small-scale sectors are generally inefficient and cause a high amount of wastage.

Fuelwood consumption and trade

Fuelwood accounts for about 48% of the total fuel consumption in rural India (FSI, 2019). It is the mainstay of India's rural population for cooking food and for other household and non-agricultural work such as rural crafts. Based on per capita fuelwood consumption, the FSI has estimated the annual consumption of fuelwood in rural areas in the vicinity of forests and non-forest areas at 78 million tonnes and 74 million tonnes, respectively. A comparative analysis using the estimates of FSI's study conducted in 2011 (ISFR 2011) shows that the fuelwood consumption in terms of per capita per year at the national level has reduced from 294.28 kg/capita/year in 2011 to 278.21 kg/capita/year in 2019, which is a reduction of 5.46%.

Fuelwood collection ("head loading") from forests is traditionally uncontrolled and unmonitored. About 75% of all forest production is said to be fuelwood, mostly collected from natural forests. Most of the 225 million m^3 of fuelwood is consumed domestically by the forest-dependent poor, including tribals. The sale of fuelwood is also a major source of income. About

ISSN: 3049-2289

30 million m^3 of fuelwood are used for industrial purposes, including charcoal.

The trade in fuelwood provides an income generation for a huge number of rural people. It has been estimated that nearly 2 to 3 million people are engaged in fuelwood collection in India, making it one of the largest sources of employment (Arnold M & *et al*., 2009). With the ease of access both to the resource and markets, a very large number of the landless and poor people gather fuelwood from the nearby forest and sell it in the market or to local people

Table 1. Trade in fuelwood

Year	Production (m^3)	Consumption (m^3)	Import	
			Volume('000 m^3)	Value('000 USD)
2019	302243688	343105	1.3	890
2020	301149640	340839	0.21	39
2021	300059215	368469	1.1	24
2022	298970266	378323	6.9	110
2023	297882823	376665	3.5	130
2024	296796915	-	1.9	2.2
2025	-	-	4.0	99

Source: Institute of Wood Science and Technology, Bengaluru, FAO and Undata

From Table 1, it is clear that production of fuelwood has decreased over the years, whereas consumption of fuelwood is increasing annually, and due to that, we can see that import of fuelwood has also increased over the years.

Detrimental outcomes of fuelwood consumption

Fuelwood collection by rural people is often cited as the most important cause of deforestation in developing countries. The type of energy utilised by households is reflection of the quality of life and socioeconomic development in any given country. Unfortunately, the continued dependence on traditional energy such as fuelwood as a major source for domestic purposes, particularly in India, is a great concern due to its negative environmental, socio-economic and health effects. The primary issues of concern include the unregulated extraction of fuelwood and the use of ineffective energy conversion technologies in households.

The major causes of concern are a lack of awareness, unsustainable harvesting, and poor technologies for energy conversion. It negatively impacts the environment, health, and the country's economic development. Each year, around 4.3 million people worldwide lose their lives prematurely due to indoor air pollution resulting from the traditional use of solid fuels (IEA, 2015). Land degradation and regional air pollution are among the environmental damage outcomes of unsustainable fuelwood consumption (NSSO, 2015).

Although wood is generally thought of as a source of trapped carbon, fuelwood consumption for a

ISSN: 3049-2289

variety of uses accounts for over 90% of emissions. The ground and middle flora of the forest have deteriorated due to the unsustainable harvesting of forest products.

Conclusion

One of the major lacunae in fuelwood management is the lack of reliable information on its collection and utilisation in the country. Therefore, there is an urgent need to develop an information repository at various levels on the fuelwood collection and utilisation patterns in the country. Although the government is trying to improve conditions through numerous new policies and interventions, the results have not been significant, and output remains well below the expected level. Fast-growing tree species should be promoted according to the site-specific climatic conditions in order to meet the fuelwood demands. Dependency of people on fuelwood could be reduced by substituting with more sustainable technologies like biogas, solar panels, etc., which will definitely lead to multiple benefits like economic, environmental protection, etc.

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CRISPR/Cas system in Plant Pathogenic Bacteria: Mechanisms and Applications

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Introduction

Crop diseases are a significant threat to global food security causing considerable economic losses and reducing agricultural productivity. According to FAO, pests and diseases are responsible for 20-40% of global food production annually with enormous economics losses. By 2050 – Global population – 9.7 billion (UN, 2019).Conventional disease management strategies, including breeding and chemical control, are often limited by time constraints, environmental concerns, and pathogen evolution. The CRISPR/Cas system, originally identified as an adaptive immune mechanism in prokaryotes, has emerged as a revolutionary genome-editing tool. This article discusses the mechanisms of CRISPR/Cas systems, their application in managing plant pathogenic bacteria, and their role in enhancing disease resistance in crops.

Conventional methods of disease resistance

- Tradition methods of managing crop diseases primarily involves breeding for resistance and application of chemical pesticides.
- This method is somewhat successful but it is time consuming and labour intensive process and may take several years and by the time pathogen may develop new strains to over come these defences
- On the other hand chemical pesticides are effective in short term in killing and inhibiting the growth of pathogen but over reliance may lead to pesticide resistance and diminishing the efficacy of it over time. Further more it can be hazardous to environment affecting the biodiversity.
- These limitations underscore the need for innovative approaches such as gene editing tool like CRISPR which offer more precise and durable solutions to enhance disease resistance in crop plants against pathogen.

What is CRISPR CAS system?

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) is a revolutionary gene editing technology was originally discovered in bacteria and archaea, where it functions as a form of adaptive immune system. These microbes use it to defend against viruses—especially bacteriophages (viruses that infect bacteria).

How It Works in Nature?

- When a virus invades, the bacterium chops up bits of the viral DNA and stores them as “spacers” in its own genome, nestled between the CRISPR repeats.
- If that virus attacks again, the bacterium transcribes these spacers into RNA.
- The RNA guides a Cas protein—most famously Cas9—to recognize and destroy matching viral DNA.
- This system gives bacteria a “memory” of past infections and a way to swiftly retaliate. Scientists cleverly adapted this natural defense into a powerful gene-editing tool for use in other organisms, including human

CRISPR/Cas9: A Timeline of Discovery and Innovation

In 1987, Yoshizumi Ishino and colleagues at Osaka University first reported unusual repetitive DNA sequences in Escherichia coli, later recognized as CRISPR elements. Subsequent studies by Francisco Mojica and his collaborators led to the characterization of these sequences and the introduction of the term "clustered regularly interspaced short palindromic repeats" (CRISPR), proposing their role as an adaptive immune system in prokaryotes (Jacinto et al. 2020). However, the functional significance of CRISPR–Cas systems was only fully elucidated in the mid-2000s, ultimately enabling their transformation into powerful genome-editing tools.

A major breakthrough was achieved by Emmanuelle Charpentier and Jennifer Doudna, who uncovered key mechanistic insights into the CRISPR–Cas9 system while investigating bacterial antiviral defense mechanisms. They identified the trans-activating CRISPR RNA (tracrRNA) as an essential component of the system and demonstrated that the CRISPR RNA (crRNA) and tracrRNA could be engineered into a single guide RNA (sgRNA). This innovation enabled the development of an RNA-programmable DNA endonuclease system capable of precise, site-specific genome editing. Furthermore, structural and biochemical studies elucidated the DNase activity and RNA-processing functions of Cas proteins, particularly Cas9, thereby facilitating its application as a versatile genetic tool. In recognition of these contributions, Charpentier and Doudna were jointly awarded the 2020 Nobel Prize in Chemistry.

Since its development, CRISPR-based technologies have rapidly advanced and diversified. The system is currently being explored in clinical settings for the treatment of genetic disorders such as sickle cell disease and various cancers. In addition to Cas9, the discovery of alternative effector proteins, including Cas12 and Cas13, has expanded CRISPR applications to encompass RNA targeting and molecular diagnostics. Moreover, catalytically inactive variants such as dead Cas9 (dCas9) have enabled epigenetic modification and transcriptional regulation without inducing double-strand DNA breaks. Collectively, these innovations have significantly broadened the scope of CRISPR–Cas systems across multiple domains, including biotechnology, medicine, and microbiology.

Key Components of CRISPR-Cas9 :

1. CRISPR: Clustered Regularly Interspaced Short Palindromic Repeats are segments of DNA containing short repetitions of base sequences. These repeats are separated by unique spacer sequences, which are derived from previous viral infections.
2. Cas9: CRISPR-associated protein 9 is an enzyme that acts as a pair of molecular scissors. It cuts the DNA double strand at a specific location guided by the CRISPR RNA (crRNA.
3. crRNA: CRISPR RNA is a short RNA sequence that is complementary to the target DNA sequence. It guides the Cas9 enzyme to the specific location on the DNA where it needs to make a cut.
4. tracrRNA: Trans-activating crRNA is a small RNA molecule that binds to the crRNA and helps it to interact with the Cas9 enzyme.

Principle

CRISPR works using a guide RNA to a target specific DNA sequence in the genome. This CRISPR is often associated with a protein known as CAS9 which makes the cut. Once the DNA is cut natural repair mechanisms are triggered allowing the Scientists to either disable genes or insert new genetic material. Thus the specific genes associated with disease susceptibility can be edited to enhance resistance in plants (Zhang et al., 2019)

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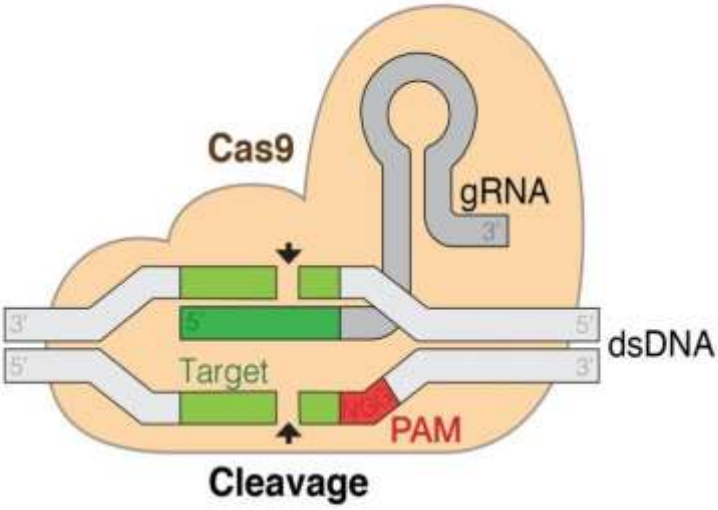
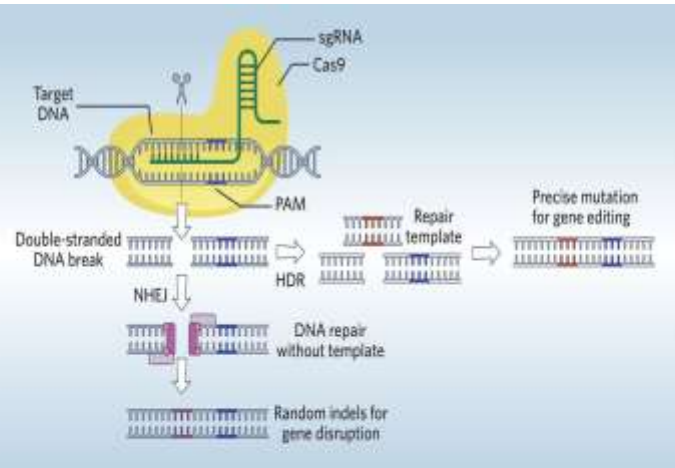


Fig.1CRISPR /CAS 9 Working principle

Fig.2. Mechanism of CRISPR/Cas gene editing



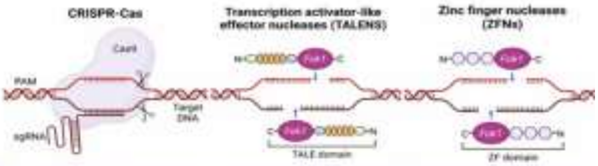
(Mac Neil and Pruller,2023)

This technology of gene editing was found in archaea and bacteria to precisely edit the genome of organism. In native system A the Cas9 enzyme is guided by a guide RNA (gRNA) duplex consisting of trans-activating CRISPR RNA(tracrRNA) and CRISPR RNA (crRNA). In the modern CRISPR/Cas technology a synthetic guide RNA used in genome editing combines tracrRNA and crRNA into single guide RNA (sgRNA). In both cases, Cas9 introduces double strand breaks (DSBs) which can be repaired through one of two mechanisms non homologous end joining(NHEJ) and homology-directed repair(HDR)

In both the native and synthetic CRISPR/Cas 9 system, a protospacer adjacent motif(PAM) act as a marker for the target site which instruct the Cas9 to cleave DNA strand at a precise location. The length of PAM is 3 – 4 nucleotides The sg RNA has a sequence homologues to the region to be cut which consist tof 10-12 base pairs Sg rana forms complex with the Cas 9 protein which cuts the DNA as double strand breaks (DSB). This will initiate the repair mechanism by two methods Non homologous end joining (NHEJ) or homology directed repair(HDR) in both cases introduce genetic alterations. NHEJ results in random insertion deletion lead to mutation due to frameshift effectively knocking out the genes.. Where as HDR allows homologous insertions of knock ins

Delivery of desired sequences or gene can be carried out by Agrobacterium mediated, bombardment mediated or PEG mediated delivery of which Agrobacterium mediated delivery is the most established one.

Comparison of CRISPR-Cas system with other gene editing tools such as TALENS and ZFNs



	CRISPR-Cas	Transcription activator-like effector nucleases (TALENS)	Zinc finger nucleases (ZFNs)
First Discovered	2012	2010	1996
Origin	Bacterial adaptive immune system	Plant pathogen proteins	Zinc finger DNA-binding domains
Guide mechanism	RNA-guided (sgRNA)	Protein-guided (TALE proteins)	Protein-guided (zinc finger proteins)
Cleavage Component	Cas9 Nuclease (HNH & RuvC domains)	FokI Nuclease Dimer	FokI Nuclease Dimer
Target recognition	20+ bp RNA-DNA complementarity + PAM	30-40 bp protein-DNA recognition	18-36 bp protein-DNA recognition
Component size	Small (~4.2 kb for Cas9)	Large (~3 kb per TALEN)	Medium (~1 kb per ZFN)
Design complexity	Low (simple sgRNA design)	Medium (modular assembly required)	High (complex protein engineering)
Assembly time	1-2 days (fast)	5-7 days (moderate)	Weeks to months (slow)
Multiplexing capability	High (multiple targets simultaneously)	Limited	Limited
Efficiency	High to Very High	High	Moderate to High (Variable)
Cost	Low	Medium	High
Specificity	Moderate to High (improving)	High	Moderate
Off-target risk	Moderate to high	Low to moderate	Low to moderate
Approved Therapies	Emerging	Limited	Limited
Applications	Dominant in research, expanding in therapeutics	Precision editing, certain therapeutic applications	Few gene therapy applications

(Al-Ouqailiet al., 2025)

wilt. The edited potatoes showed a remarkable decrese in disease severity and improved survival rates under conditions of high pathogen pressure.

- Similarly, in tomatoes, CRISPR enhanced bacterial blight resistance caused by *Pseudomonas syringae* Zhang *et al*., 2020 targeted the SIPto gene in tomato which encodes a receptor that recognises specific bacterial effector molecules. By utilising the CRIPR/Cas9 they successfully edited this gene, resulting in tomatoes with bacterial blight resistance. The plant exhibited reduced symptoms and produced higher yield

Development of resistance against citrus canker bacteria has been done by CRISPR/CAS9 in grape fruits and oranges.

- This can be done by modifying the promoter of the latera; organ border gene (LOB) gene. The primary transcription activator –like(TAL) effector of *Xanthomonas citri* subsp. *citr*i (Xcc) known as PthA4 binds specifically to the effector binding element, EBEPthA4, in the LOB promoter. This binding activates gene expression and causing citrus canker. Mutations in EBEPthA4 can reduce or eliminate the PTHA4 inducible activity of LOB promoter thereby enhancing the resistance
- TAL effector of *Xanthomonas oryzae* pv. *Oryzae* known as PthXo1, binds to the effector binding element, EBEPthXo1, in the promoter region of Os8N3, a member of the SWEET family of sugar transporters. This interaction promotes bacterial blight disease in tomatoes. By using CRISPR/Cas(to disrupt the SWEET gene plant can achieve increased tolerance to bacterial blight.

Applications

- **Targeted Gene Editing -Disrupting Pathogen Receptor Genes**

Pathogens often exploit specific plant receptors to gain entry and infect the host.CRISPR-Cas9 can be used to precisely inactivate these receptor genes, effectively blocking the pathogen's entry point.This strategy has been successfully applied in various crops, such as rice and tomato, to confer resistance against fungal and bacterial diseases.

- **Enhancing Immune Response Genes**

Plants possess innate immune systems that recognize and defend against pathogens. CRISPR-Cas9 can be used to:

a) **Enhance the activity of existing immune genes**: By introducing mutations that increase gene expression or protein activity.

b) **Introduce new immune genes**: From other plant species or even other organisms, providing broader resistance.

- **Modifying Pathogen-Derived Effectors**

Many pathogens secrete effector proteins that suppress plant immunity. CRISPR-Cas9 can be used to target and disrupt these effector genes within the pathogen itself, weakening its ability to infect the host.

- **Developing Broad-Spectrum Resistance Editing Multiple Genes**

Plant diseases often involve complex interactions between the pathogen and the host CRISPR-Cas9 allows for simultaneous editing of multiple genes involved in different aspects of disease resistance, providing a more robust and durable defense

- **Engineering Resistance to Emerging Diseases**

The rapid emergence of new plant diseases poses a significant challenge to global food security CRISPR-Cas9 can be used to rapidly develop resistance to these emerging threats, significantly reducing the time required for traditional breeding methods

- **Enhancing crop resilience**

It can be utilised to develop crop varieties that are better suited for organic farming systems which mainly rely on natural pest management and nutrient recycling. Editing genes related to drought tolerance, nutrient use efficiency and disease resistance can lead to crops that require fewer resources and are more resilient to environmental stresses. Thus improving overall health of agro ecosystem and reduces the dependency to synthetic fertilisers and pesticides

- **Promoting Biodiversity**

CRISPR can facilitate preservation of biodiversity by enabling the development of heritage and underutilized crop varieties that are more resistant to local pests and diseases.

Advantages

- Precision: Highly specific targeting of desired genes.
- Efficiency: Enables rapid and efficient generation of disease-resistant plants.
- Versatility: Applicable to a wide range of plant species and diseases.
- Flexibility: Allows for various types of genetic modifications, including gene knockouts, insertions, and modifications. By leveraging the power of CRISPR-Cas9, scientists are developing innovative and sustainable solutions to combat plant diseases, ensuring a more secure and abundant food supply for the future.

Unlike traditional breeding methods which are time consuming and limited by plants's natural gene pool, CRISPR allows for rapid and precise edits that can overcome the evolving nature of pathogens. Moreover, CRISPR technology minimizes the need for chemical pesticides making it more environmentally sustainable option. Hence it offers immense potential; in improving crop health and contributing to global food security through better disease management

- Reducing crop loss and increase yield
- Disease resistance and crop resistance
- Improved food security
- Sustainability and environmental benefits
- Reducing the need for chemical pesticides and inputs
- Covering farming costs
- Enhanced resistance to local diseases
- Economical and social benefits

Challenges

1. Off-Target Effects

- Unintended Mutations: The CRISPR-Cas9 system, while highly specific, can occasionally target unintended DNA sequences with similar sequences to the intended target. This can lead to unintended mutations, potentially causing undesirable traits or even harm.
- Minimizing Off-Target Effects: Researchers are actively developing strategies to minimize off-target effects, such as using modified Cas9 enzymes with increased specificity and employing computational tools to predict and avoid potential off-target sites.

2. Regulatory Hurdles

- GMO Regulations: In many countries, CRISPR-Cas9 edited plants are subject to the same regulations as traditional genetically modified organisms (GMOs). This can involve lengthy and costly regulatory processes, hindering the development and commercialization of these technologies.
- Differentiated Regulation: There is a growing movement to differentiate between CRISPR-Cas9-edited plants that do not contain foreign DNA and traditional GMOs. This could streamline

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the regulatory process and accelerate the adoption of these technologies.

3. **Public Perception**

- Fear of the Unknown: Public perception of GMOs can be a significant obstacle, with concerns about potential risks to human health and the environment.
- Educating the Public: Effective communication and public education are crucial to address public concerns and build trust in CRISPR-Cas9 technology. Transparent and open discussions about the benefits and risks of this technology are essential.

4. **Ethical Considerations**

- Unforeseen Consequences: While CRISPR-Cas9 offers significant benefits, it is crucial to consider potential long term ecological and societal impacts.
- Responsible Innovation: It is essential to ensure that CRISPR-Cas9 technology is used responsibly and ethically, with careful consideration of potential risks and benefits.

5. **Technical Challenges**

- Efficient Delivery: Delivering the CRISPR-Cas9 components effectively into plant cells can be challenging.
- Precise Editing: Achieving precise and predictable edits in complex plant genomes can be difficult.
- Species-Specific Challenges: The efficiency and specificity of CRISPR-Cas9 can vary depending on the plant species. Addressing these challenges requires
- Continued Research: Continued research is necessary to improve the specificity and efficiency of CRISPR-Cas9, minimize off-target effects, and develop more efficient delivery methods.
- Regulatory Reform: Regulatory frameworks need to be updated to reflect the unique characteristics of CRISPR Cas9-edited plants.
- Public Engagement: Open dialogue and public engagement are crucial to build trust and ensure responsible innovation.

Conclusion

In an era of escalating global food demands and emerging plant diseases, the development of robust and sustainable disease resistance strategies is paramount. Traditional breeding methods, while valuable, often prove inadequate in the face of rapidly evolving pathogens and the increasing urgency of food security challenges. The advent of CRISPR-Cas9 technology offers a transformative approach to plant disease control, providing unprecedented precision and efficiency in manipulating plant genomes. By precisely targeting and modifying genes involved in pathogen susceptibility, enhancing immune responses, and disrupting pathogen virulence factors, CRISPR-Cas9 empowers scientists to engineer plants with durable and broad-spectrum resistance against a wide range of diseases. This technology holds the potential to accelerate the development of disease resistant varieties for major crops, mitigating yield losses and ensuring a stable and secure food supply. Addressing the risk of off-target effects through refined gRNA design and robust screening methods is crucial.

Future prospects

Targeting of CRISPR interventions and Integrating CRISPR with AI and Big Data enhanced Real time monitoring of plant health. CRISPR- Cas variants and new generation editing tool for improvement eg: CRISPR-Cas 12 creates staggered cuts in DNA which facilitate more precise insertions of new genetic material enhancing the efficiency of gene editing. Additionally it is capable of targeting multiple gene simultaneously making it a powerful tool for developing crops with complex traits such as

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multiple gene disease resistance or improved stress tolerance.

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Conservation Agriculture – Importance and Impact on Soil Properties

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Introduction

Conventionally managed agriculture systems are marked by intensive tillage, fixed cropping, crop residue burning, promiscuous use of irrigation water as well as chemical fertilizers. Continued adoption of this has resulted in diminished factor productivity, degrading soil health and a reduction in soil organic matter. Furthermore, it has contributed to issues such as soil salinization, contamination in surface and groundwater and an escalation in operational expenses, ultimately stifling profit margins.

It is realized that abandoning methods like mulching, intercropping, and legume rotation has led to situation where soil is undergoing progressive nutrient exhaustion. Furthermore, the utilization of organic amendments, including manures, composts, and green manures, has seen a marked decline. Concurrently, the combustion of fossil fuels and agricultural residue, puddling under paddy cultivation significantly contributes to release of greenhouse gases, thereby driving anthropogenic climate change and global warming.

There is a growing concern that traditional agricultural methods lack long-term viability. Consequently, a fundamental shift in traditional approach to manage arable lands sustainably is the need of hour. Conservation agriculture (CA) has emerged as a transformative framework for resource optimization, specifically designed to mitigate the systemic inefficiencies inherent in conventional intensive cultivation. CA is described by FAO (http://www.fao.org.ag/ca) as a concept for resource saving agricultural crop production which is based on enhancing the natural and biological processes above and below the ground. It can also be termed as "resource efficient" or "resource effective agriculture".

Three principles of CA are: (i) minimal mechanical soil disturbance, (ii) maintenance of permanent soil organic cover, and (iii) crop diversification. These fundamental principles apply to all types of agricultural land, though the actual techniques must be customized and integrated based on local requirements. Like, adopting a single intervention, such as zero tillage (ZT), is insufficient for a system to be categorized as conservation agriculture; rather, it must be integrated with permanent soil cover via mulching and a varied crop rotation. Unlike conventional tillage systems, CA requires site-specific modifications to water and fertilizer use, pest control, and weed management and also in farm machinery. CA enhances soil health by fostering diverse biological activity and strengthening its physical properties by creating a natural shield of mulch layer that protects soil surface from direct impact of rain, while buffering it against extreme temperature and moisture changes. CA achieve a balance of agricultural and economic benefits by optimizing the yields and profits, while protecting the environment.

Currently, the widespread adoption of mechanized harvesting has posed the great challenge of in-situ residue burning across the nation, despite government regulations and financial incentives. This detrimental practice results in substantial depletion of essential soil nutrients and elevates environmental pollution. Consequently, pioneering strategies are now required to address these agriculture complications within changed circumstances.

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CA basically relies on 3 principles, which are linked and must be considered together for appropriate design, planning and implementation processes. These are:

	**Minimum mechanical soil disturbance** (i.e. zero/ reduced tillage)
	**Permanent soil organic cover** (minimum 30% crop residue)
	**Crop diversification** (crop rotations including minimum 3 different crops)

Fig.1. Principles of Conservation Agriculture

1. **Minimum Mechanical soil disturbance** – Utilizing reduced or zero-tillage (RT/ZT) techniques to ensure minimal soil disturbance is essential for preserving soil health, as it prevents the breakdown of soil structure and protects surface organic matter. These practices support ecological conservation and agricultural longevity by maintaining the soil structure, stimulating microbial processes, and facilitating the sequestration of organic carbon.
2. **Permanent soil organic cover** – Maintaining a consistent soil cover through application of organic mulches, crop leftovers, or perennial cover crops protect the soil against erosive forces of precipitation and solar radiation. This permanent cover ensures a steady substrate supply for soil biota while moderating the microclimate to facilitate the optimal proliferation of microbial communities and root systems.
3. **Crop diversification** – It serve as more than just a nutritional variety for soil biota; it facilitates the recovery of nutrients leached into deeper profiles, allowing deep-rooted species to recycle the minerals that are otherwise inaccessible. Legume based cropping systems mitigates pest population surges by interrupting their life cycles while simultaneously fostering biological nitrogen fixation; furthermore, they enhance ecological biodiversity and provide a buffer against off-site environmental pollution.

1. Effects of CA on soil physical properties -

1.1. Soil Structure - Soil structure affects various physico-chemical, and biological processes, while also dictating the vulnerability towards water erosion. CA practices reinforce topsoil structure by enhancing aggregate stability and mitigating risk of compaction. This improvement is primarily driven by accumulation of surface organic matter, which functions as a structural buffer that dissipates the kinetic energy of raindrops and reduces erosive impact. A long-term experiment showed CA with maize cultivation can improve soil structure by altering its hydraulic properties.

1.2. Bulk Density - Bulk density is a representative of soil compaction and its ability to seedling emergence, root proliferation, and overall crop yield. Certain studies indicated an increase in bulk density compared to intensive tillage system, while others found no significant variation or even reduction in bulk density under CA. No-tillage systems with residue incorporation demonstrated a small 1.4% increase in soil bulk density compared to conventional tillage.

1.3. Water Infiltration, Retention and soil erosion - Conservation tillage practice enhances structural stability of soil and improves infiltration and water holding capacity due to enhanced porosity, aggregate distribution and reduced compaction, soil erosion (upto 80%) and runoff (up to 50% decrement) compared to conventional tillage.

2. Effects of CA on Soil Chemical Properties -

2.1 Soil Organic Carbon – CA improves soil health and quality through increasing organic matter and plant available nutrient content. CA increases SOC up to 20-40% in surface layer (0-30 cm) in 5-7 years period due to RT with residue retained on surface and can sequester about 2 Mg ha^{-1} of SOC in top soil layer (0-15 cm).

2.2 Soil pH - Decomposition of plant residue produces organic acids that can alter soil reaction. However, its influence varied depending upon soil, climate, and different residue management interventions. CA practices like no-till, minimum tillage with residue retention reported to lower the pH. On the contrary crop residue in permanent beds raises pH compared to conventional systems.

2.3 Cation Exchange Capacity (CEC) – CA practices enhance SOC which effects soil's CEC. Addition of organic residue increases organic matter (humus) in soil which has the highest CEC (>200 cmol p^+ kg^{-1}soil) and natural capacity to hold and exchange nutrients. Therefore, reduced leaching and increased retention of nutrients.

2.4 Nutrients Cycling – Diversified crop rotation under CA improves nutrient cycling through facilitating different nutrient needs and root morphology of various crops. Inclusion of legumes enhances nutrient cycling through their ability to fix atmospheric nitrogen and continuous soil organic cover with ZT optimize soil temperature and moisture which reduces volatilization and denitrification losses of nitrogen. Improved phosphorus availability under CA may be attributed binding of released organic acids with P immobilizing compounds (iron and aluminium) upon residue decomposition. Additionally improved CEC under CA helps retaining more potassium (K), calcium (Ca), and magnesium (Mg), ammonium (NH_4^+). Organic matter, a substrate for soil biota increases their population which governs mineralization and immobilization of nutrients in soil.

2.5 Mitigating Climate Changes and Greenhouse Gas Emissions (GHG) and carbon sequestration - CA management practices like zero or reduced tillage, soil organic cover and crop diversification like inclusion of legumes has gaining attention due to their great potential to mitigate climate change and deducing GHG emissions by sequestering carbon from atmosphere and reduced mineralization, supplementing the CO_2 produced within the agricultural sector. Additionally reduced denitrification loss under CA accounts for 11% lower N_2O emission.

3. Effects of CA on Soil Biological Properties -

3.1 Microbial Biomass – It is a positive indicator of soil health which dominantly include bacteria and fungi. CA practices by increasing SOC and improving soil physico-chemical and biological traits, creates an environment that supports higher microbial biomass to enhance soil health. Soil fauna is critical to the maintenance of soil fertility and enhanced plant growth. CA, alongside its benefits for microbes, greatly helps soil fauna including earthworms, insects, and predatory spiders by providing improved habitat and food sources through reduced disturbance and organic residues. Through their natural processes, soil fauna actively decomposes organic matter, facilitate nutrient cycling, and enhances soil structure.

3.2 Enzyme activity - Studies have indicated that CA improves soil enzyme activity, a key determinant of soil health and fertility. Increased enzyme activity accelerates SOC decomposition and nutrient cycling processes, which are fundamental for sustaining crop productivity and soil health. For example, under CA practices increases of β-glucosidase and arylsulfatase enzyme activities associated with improved SOM content and nutrient availability. These results reveal the significant advantages of implementing CA to maintain a healthy soil, enhance biological

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processes within the soil, and contribute to overall agricultural sustainability.

Conclusions

Conservation agriculture represents a fundamental departure from traditional research framework in India, which historically prioritized quantitative research production targets over ecological stability. This paradigm shift is now imperative, as past strategies aimed at maximizing yields have inadvertently triggered widespread resource degradation and compromised soil integrity. Sustaining future productivity growth now necessitates a holistic integration of yield stability, resource conservation, and environmental health. Advancing CA systems requiring a strong knowledge base and a transition toward a systems perspective in scientific research, fostered by participatory engagement with farmers and enhanced information sharing networks. Ultimately, CA provides a strategic pathway to reverse the current trend of land degradation, optimize production costs, and ensure that Indian agriculture remains resource efficient, competitive, and ecologically resilient.

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Beyond Sugarcane: How Kestur is Reimagining Farming in Water-Stressed Karnataka

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Farmers in Mandya district are gradually shifting from water-intensive sugarcane to diversified crops such as ragi, pulses, and vegetables.

Mandya district, long known as Karnataka's "Sugar Bowl," has for decades drawn its agricultural strength from sugarcane. Fed by the canals of the Krishna Raja Sagara (KRS) Dam, vast stretches of farmland once stood as symbols of irrigation-led prosperity.

But in Kestur village of Maddur taluk, a quiet shift is taking root—one that reflects the changing realities of water, soil, and survival.

A system under strain

Sugarcane has historically been the backbone of Mandya's rural economy. With assured procurement from nearby mills and relatively predictable irrigation, farmers in villages like Kestur built their livelihoods around a single crop.

Yet this dependence came at a cost.

Sugarcane is among the most water-intensive crops, requiring between 1,500 and 2,500 mm of water per crop cycle, according to the Food and Agriculture Organization. As rainfall patterns have become erratic and canal water less reliable, farmers—especially those at the tail end of irrigation networks—have struggled to sustain yields.

Soil health has also deteriorated under continuous monocropping. Heavy reliance on chemical fertilizers and pesticides has increased costs while reducing long-term productivity. Delayed payments from sugar mills have further strained farm incomes, exposing the fragility of the system.

Small changes, significant impact

The shift in Kestur did not begin with policy mandates, but with individual choices.

Faced with uncertainty, some farmers began experimenting with alternatives—initially on small portions of land. Crops such as ragi (finger millet), pulses, and seasonal vegetables like brinjal and tomatoes gradually entered the farming cycle.

These experiments yielded encouraging results.

Ragi, a traditional staple in Karnataka, proved resilient under low-water conditions. Agricultural research bodies such as the Indian Council of Agricultural Research highlight millets as climate-resilient crops that require fewer inputs while supporting sustainable farming.

Pulses contributed to soil health by naturally fixing nitrogen, reducing dependence on synthetic fertilizers. Vegetables, with shorter growing cycles, provided quicker and more frequent income compared to sugarcane's long harvest period.

Restoring balance in the fields

Diversification has triggered broader ecological benefits.

Crop rotation has helped restore soil structure and nutrient balance, while reducing pest cycles. Farmers report a gradual decline in input costs as dependence on chemicals decreases.

Water use, once a persistent concern, is also becoming more efficient. Under schemes such as the Pradhan Mantri Krishi Sinchayee Yojana, micro-irrigation practices like drip systems are gaining ground, enabling farmers to make better use of limited water resources.

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Learning from each other

In Kestur, change has spread informally.

Farmers have relied on peer learning—sharing experiences, discussing outcomes, and adapting practices collectively. This exchange of knowledge, built on trust, has played a crucial role in expanding diversification across the village.

Institutional support has followed. Extension services and agricultural experts have introduced integrated nutrient management, organic inputs, and eco-friendly pest control methods, strengthening farmers' confidence in sustainable practices.

Case Study 1: Collective Strength through an FPO

A major turning point in Kestur's transition came with the emergence of a Farmer Producer Organization (FPO), supported by institutions such as the Small Farmers Agribusiness Consortium and the National Bank for Agriculture and Rural Development.

Bringing together around 120 small and marginal farmers, the FPO enabled collective cultivation and marketing of ragi and pulses. Instead of selling individually to local traders, farmers began aggregating their produce and negotiating directly with buyers in urban markets like Bengaluru and Mysuru.

This shift resulted in:

- Improved price realization through collective bargaining
- Reduced transportation costs via shared logistics
- Access to institutional and bulk buyers

The FPO also introduced basic processing such as cleaning and grading, enhancing the quality and market value of millets. For many farmers, this marked a shift from subsistence-level selling to participation in structured value chains.

Case Study 2: Vegetable Cluster and Water Efficiency Initiative

Another example of grassroots innovation is seen in a vegetable cultivation cluster formed under the FPO framework.

Supported by the Pradhan Mantri Krishi Sinchayee Yojana and guided by experts from the Indian Council of Agricultural Research, around 40 farmers adopted drip irrigation systems for crops such as tomato, chilli, and beans.

The initiative focused on:

- Efficient water use, reducing consumption by up to 40–50%
- Integrated pest management practices
- Crop planning aligned with market demand

The FPO facilitated market linkages, helping farmers connect with wholesalers and retailers while reducing dependence on intermediaries.

Within a few cropping cycles, farmers reported:

- More regular and diversified income streams
- Lower input costs due to efficient resource use
- Reduced risk compared to reliance on a single crop

New markets, new momentum

Market trends have also worked in farmers' favour.

Millets such as ragi are witnessing renewed demand, driven by growing awareness of their nutritional value and environmental sustainability. Government initiatives promoting millets have further expanded market opportunities.

What was once seen as a subsistence crop is now positioned as a viable and future-ready alternative.

The road ahead

The transition is not without challenges.

Vegetables require reliable storage and transport infrastructure, which remains limited in many rural areas. Price fluctuations and market access continue to pose risks. Diversified farming also demands greater planning and labour, making it more complex than monocropping.

Even so, the shift in Kestur is gaining momentum**.**

A model of quiet resilience

What distinguishes Kestur is not just the crops its farmers grow, but the thinking that guides their decisions.

There is a growing recognition that long-term sustainability—of soil, water, and income—must take precedence over short-term gains. In the face of climate uncertainty, diversification is emerging not as an option, but as a necessity.

Kestur's experience offers a broader lesson for Indian agriculture. Transformation need not always be driven by large-scale reforms. It can begin at the grassroots, with farmers willing to adapt, experiment, and share knowledge.

In the fields of this Mandya village, a new agricultural story is unfolding—one defined not by dependence, but by diversity and resilience.

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Bridging the Gap: Strengthening KVKs for Effective Extension Services in Arunachal Pradesh.

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Introduction to KVK

One of the major constraints in Indian agriculture is the gap between research institutions and field-level application. Agricultural technologies developed in laboratories often fail to reach farmers effectively due to weak extension systems. To strengthen the agricultural extension system and improve the transfer of technology to farmers, the Indian Council of Agricultural Research has established Krishi Vigyan Kendras (KVKs) at the district level as farm science centres for the effective dissemination of scientific knowledge and agricultural innovations.

In Arunachal Pradesh, a total of 17 KVKs operate under ICAR, the State Government, and Central Agricultural University, coordinated by ICAR-ATARI Zone VI, Guwahati. These KVKs are strategically located across districts such as Anjaw, West Siang (Basar), West Kameng (Dirang), Lower Subansiri, Papumpare, and others addressing the region's unique agricultural challenges. Given the state's hilly terrain, ecological diversity, and predominance of tribal farming systems, KVKs play a critical role in delivering location-specific and need-based interventions. They promote the adaptation of improved agricultural technologies while integrating indigenous knowledge systems.

Role of KVKs in Strengthening Extension Services

Krishi Vigyan Kendras (KVKs) are district-level agricultural innovation and extension units under the national agricultural research system. Their primary mandate is technology assessment, refinement, and frontline demonstration to validate agricultural innovations under real farm conditions before dissemination. This ensures the adaptation of research outputs to local agro-ecological contexts and improves their field-level applicability. The KVK system has evolved from a vocational training model into a key mechanism linking agricultural research and extension, incorporating earlier initiatives such as National Demonstrations and Lab-to-Land programmes.

In Arunachal Pradesh, KVKs are particularly significant due to diverse agro-climatic conditions and predominantly subsistence tribal farming. They conduct on-farm trials and demonstrations of improved crop varieties, livestock practices, and sustainable farming systems suited to hill agriculture. In addition, it provides capacity building for farmers, rural youth, and women, and deliver advisory services on soil health, pest management, weather-based farming, and market information. They also promote climate-resilient and sustainable practices, including organic and climate-smart agriculture, to enhance productivity and livelihood security in the region.

Role in Technology Transfer

KVKs play a key role in testing and demonstrating new agricultural technologies directly on farmers' fields. Through **frontline demonstrations (FLDs)** and **on-farm testing (OFTs)**, they show the benefits of improved varieties, fertilizers, and management practices. This helps farmers gain confidence and encourages faster adoption of innovations.

Frontline Demonstrations (FLDs)

KVKs conduct Frontline Demonstrations to showcase the effectiveness of improved technologies directly on farmers' fields. These demonstrations

ISSN: 3049-2289

help farmers visually understand the benefits of new practices, thereby increasing their confidence and encouraging adoption at a larger scale.

Capacity Building and Training

Krishi Vigyan Kendras (KVKs) play a vital role in capacity building by conducting need-based and locally relevant training programmes for farmers, farm women, rural youth, and extension personnel. These trainings focus on strengthening practical and technical competencies, while also promoting awareness about crop selection based on soil type, nutrient status, and local agro-ecological conditions. By providing skill-oriented training, KVKs enable farmers to adopt appropriate cropping systems and improve productivity through informed decision-making. They also encourage diversification into allied sectors such as livestock, horticulture, and agri-based enterprises, thereby supporting entrepreneurship development. Overall, these interventions contribute to increased income generation, employment creation, and sustainable livelihood diversification in rural areas.

KVK as Knowledge and Resource Centre

Krishi Vigyan Kendras (KVKs) function as district-level single-window knowledge and resource centres that provide integrated services including technical advisory support, access to quality inputs, and need-based agricultural guidance. They also utilize information and communication technology (ICT) tools to disseminate scientific information efficiently, thereby strengthening their role as decentralized knowledge hubs for farmers.

Institutional Linkages and Convergence

Institutional linkages and convergence are critical components of an effective agricultural extension system. The analysis underscores that coordinated interaction among Krishi Vigyan Kendras (KVKs), research institutions, government departments, financial institutions, and non-governmental organizations enhance the efficiency and impact of extension services. Strengthening these linkages minimizes redundancy, optimizes resource utilization, and facilitates the integrated delivery of services.

Furthermore, such convergence ensures that farmers receive comprehensive support encompassing capacity building, access to credit, technology dissemination, and market linkages. A collaborative, multi-stakeholder approach thus contributes to improved service delivery, greater coherence in program implementation, and more sustainable agricultural development outcomes.

Impact on Farmers and Rural Communities of Arunachal Pradesh

Krishi Vigyan Kendras (KVKs) have demonstrated a measurable positive impact on agricultural productivity, farm income, and the adoption of improved technologies. Direct beneficiaries of KVK interventions gain through training, demonstrations, and advisory services, while indirect diffusion occurs via farmer-to-farmer interactions and local social networks. This process of knowledge spillover accelerates the dissemination of innovations, leading to broader improvements in agricultural practices and overall regional performance.

In Arunachal Pradesh, KVKs play a particularly significant role due to the state's complex topography, heterogeneous agro-climatic conditions, and predominance of tribal farming systems. These institutions facilitate the transition from traditional practices such as shifting cultivation (jhum) to more sustainable and productivity-enhancing approaches. They promote diversification into horticulture and high-value cash crops, while also delivering location-specific technologies and management practices tailored to the unique ecological conditions of the region.

Challenges Faced by KVKs in Arunachal Pradesh

KVKs in Arunachal Pradesh face multiple constraints, including limited manpower, inadequate funding, and weak physical and digital infrastructure. The state's rugged terrain, scattered settlements, and

ISSN: 3049-2289

poor road connectivity make regular outreach and timely service delivery difficult. Low levels of mechanization, limited input availability, and weak market linkages further restrict the adoption of improved technologies. The predominance of subsistence farming, along with low farmer awareness and interest, reduces participation in training and extension programmes. Traditional practices such as jhum cultivation and risk aversion also slow the shift toward modern, market-oriented agriculture. Institutional challenges such as weak coordination among departments, language and cultural diversity, and limited use of ICT tools also affect extension efficiency. Addressing these issues requires strengthening infrastructure and staffing, improving last-mile connectivity, promoting market access, enhancing farmer motivation through demonstrations and incentives, and ensuring better convergence among stakeholders for more effective service delivery.

Need for Strengthening KVKs

Strengthening KVKs is crucial for improving agricultural extension in Arunachal Pradesh, where challenging terrain, diverse agro-climatic conditions, and traditional farming systems require location-specific approaches. Enhancing infrastructure, funding, skilled manpower, and ICT use can significantly improve outreach and service delivery. Stronger institutional linkages will also ensure better technology transfer and farmer support.

Strategies for Strengthening KVKs of Arunachal Pradesh

- **Location-specific technologies:** Develop and promote crop varieties, livestock practices, and farming systems suited to hill agriculture and diverse micro-climates.
- **Strengthening last-mile connectivity:** Use mobile advisory services, community radio, and offline digital tools to reach remote and tribal areas.
- **Capacity building of farmers:** Conduct need-based, participatory training in local languages to improve awareness and adoption.
- **Promotion of climate-resilient agriculture:** Encourage integrated farming systems, soil and water conservation, and agroforestry practices.
- **Diversification and high-value crops:** Promote horticulture, spices, medicinal plants, and niche products suited to the region.
- **Support for farmer organizations:** Strengthen Farmer Producer Organizations (FPOs) and self-help groups to improve market access and collective action.
- **Market and value chain development:** Facilitate linkages for storage, processing, and marketing to enhance income from surplus production.
- **Incentivizing youth and agripreneurship:** Encourage rural youth through skill development, startups, and agri-based enterprises.
- **Improved transport and demonstration units:** Establish cluster-based demonstration farms and mobile KVK units to overcome geographical barriers.
- **Stronger convergence:** Enhance coordination with line departments, NGOs, and financial institutions for integrated service delivery.

These strategies can improve the effectiveness of KVKs, promote technology adoption, and support sustainable agricultural and rural development in Arunachal Pradesh.

Conclusion

Krishi Vigyan Kendras (KVKs) form a cornerstone of India's agricultural extension system by effectively linking research with farmers through technology assessment, frontline demonstrations, training, and advisory services. They play a vital role in enhancing productivity, increasing farm income, and improving rural livelihoods.

In regions like Arunachal Pradesh, their importance is even greater due to challenging terrain, diverse agro-climatic conditions, and traditional farming systems. Strengthening KVKs through better infrastructure, skilled manpower, ICT integration, and stronger institutional linkages can significantly enhance their outreach and impact. Overall, a well-supported KVK system can accelerate agricultural growth, promote sustainable practices, and contribute to inclusive rural development.

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Beyond the Spray
From Production to Realisation: Fixing India's Farm Economy

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India's agricultural economy is entering a structural transition. For decades, the industry's primary objective was to improve productivity. Better seeds, fertilizers, irrigation systems, and crop protection molecules were developed to maximize yield per acre. By many measures, this mission succeeded. India today stands among the world's largest agricultural producers and has also emerged as the third-largest agrochemical exporter globally.

Yet beneath this production success lies an uncomfortable reality: farmer income remains deeply unstable.

This contradiction is becoming increasingly visible across the agricultural landscape. Record crop output is often accompanied by falling mandi prices, distress selling, delayed procurement, and weakening rural purchasing power.

The implication for agrochemical companies, investors, and policymakers is profound. The next phase of agricultural growth will not be driven merely by yield enhancement. It will be driven by systems that improve farmer realization and income stability.

The future of agriculture will be defined not by who helps farmers grow more, but by who helps them earn better.

India's Agri-Paradox: Higher Output, Lower Financial Stability

India's agricultural production continues to scale. Foodgrain and horticulture output have touched record highs in recent years, supported by favorable monsoons, subsidies, and widespread input availability.

At the same time, many farmers continue to sell below Minimum Support Price (MSP), particularly in crops where procurement mechanisms are weak or absent.

This paradox highlights a fundamental flaw in the agricultural value chain: production and monetization are treated as separate problems.

The industry focuses heavily on the first half of the cycle—inputs, crop protection, yield enhancement, and agronomic efficiency. But the farmer's financial outcome is ultimately determined in the second half—market access, timing of sale, liquidity pressure, and price realization.

In practical terms, a farmer can achieve excellent productivity and still experience financial distress if prices collapse during harvest season.

This pattern is no longer theoretical it is playing out across India. In Uttar Pradesh's Amroha district, cauliflower farmers recently chose to run tractors over standing crops when mandi prices crashed to nearly ₹1 per kilogram. The cost of harvesting and transporting the produce was higher than what the market was willing to pay. In Madhya Pradesh, banana growers have destroyed fully grown crops because there were no buyers at viable prices. In Maharashtra, an onion farmer who spent tens of thousands on cultivation reportedly received only a few hundred rupees after selling his produce in the mandi. In some soybean-growing regions, farmers have even avoided harvesting altogether, as the expected price could not justify the cost of labor.

In all these cases, one factor remained constant: the input cost was real, capital-intensive, and unavoidable. Seeds were purchased, fertilizers applied, and crop protection measures followed. Yet,

ISSN: 3049-2289

at the moment of realization, the farmer earned almost nothing.

Yield is a technical outcome. Income is a market outcome.

The Commoditization Crisis in Agrochemicals

The Indian agrochemical industry itself is undergoing rapid transformation. The market has expanded significantly over the past decade, driven by both domestic demand and export growth.

However, the market structure has fundamentally changed. Generic molecules are now widely available, and almost every company offers similar formulations. This has intensified price competition and reduced brand differentiation.

The consequences are visible across the value chain. Dealers increasingly influence purchase decisions based on margins and credit cycles. Farmers perceive products as interchangeable. Companies rely on schemes, discounts, and incentives to sustain market share.

In such a market, differentiation through chemistry alone becomes difficult. When every company has access to the same molecule, the battle shifts from product to ecosystem.

The Real Problem Farmers Face Is Not Growing — It Is Selling

Over the years, Indian farmers have become more technically capable. Access to agronomy advice, digital content, and input products has improved significantly. Most farmers today understand spray schedules, nutrient management, pest cycles, and yield optimization practices.

But their biggest challenge begins after harvest.

During crop growth, farmers retain flexibility. They can delay spraying, adjust dosage, or even re-sow in early stages. After harvest, that flexibility disappears. The crop cannot wait. The creditor cannot wait. The household expenses cannot wait.

This creates immediate selling pressure. Farmers often sell not because prices are favorable, but because liquidity is urgent. In many cases, they have taken inputs on credit during the crop cycle and must repay immediately after harvest, leaving little room to wait for better prices.

The farmer has control during cultivation, but loses control at realization.

Distress Selling Is a Structural Outcome, Not a Farmer Failure

Agricultural price volatility is often misunderstood as a temporary market issue. In reality, it is deeply structural.

Several factors influence realization simultaneously—arrival volumes, weather patterns, policy decisions, trader sentiment, procurement capacity, and storage availability.

This means farmers are exposed to risks far beyond their control. Even a well-managed crop cannot protect against market collapse.

The earlier examples of crop destruction and distress sales are not isolated incidents. They are symptoms of a system where production is incentivized, but realization is neglected.

Distress selling is not a production problem. It is a systems problem.

Why the Industry Must Expand Beyond Pre-Harvest Engagement

Traditionally, agrochemical companies focus heavily on pre-harvest engagement—field demonstrations, advisory services, and product positioning. However, engagement sharply declines after harvest.

This creates a strategic gap.

From a farmer's perspective, the value of any agricultural input is ultimately judged through one question: did it improve my income?

If higher yield results in weak realization, the perceived value of the input declines. Over time, this erodes trust.

Trust in agriculture is not built during spraying. It is built after selling.

The Shift From Product Companies to Income Ecosystems

The future of the industry lies in ecosystem creation.

This does not mean agrochemical companies must become traders or adopt contract farming models. Those approaches carry their own complexities. Instead, the opportunity lies in enabling post-harvest support systems—market linkages, price intelligence, aggregation, storage advisory, and digital selling platforms.

Even small improvements in realization can have a disproportionate impact on farmer income. A 5–10% increase in price often matters more than marginal gains in yield.

The Farmer Income Cycle: A New Strategic Lens

To understand the future direction of agriculture, it is useful to frame the sector through the Farmer Income Cycle:

Input → Crop → Harvest → Pressure → Realization

The industry has historically focused on the first three stages. But the last two stages determine financial outcomes.

Pressure includes debt repayment, liquidity needs, and household expenses. Realization determines whether the season results in profit or distress.

This is where the greatest opportunity for innovation now exists.

Conclusion

India's agricultural sector is entering a new phase of evolution. The first phase solved for production. The second phase must solve for income.

This transition will reshape how companies compete, how investors evaluate opportunities, and how value is created across the ecosystem.

The future belongs to organizations that understand a simple but transformative reality: Farmers do not buy products. They buy the possibility of a better financial outcome.

The agrochemical industry has already helped India grow more.

The next challenge is far more important—helping farmers earn better.

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Specialty paper from mulberry (*Morus* sp.) for making art and crafts

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Mulberry paper is a kind of superfine writing paper of medium to heavy basis weight, slightly modified for better folding. The finish is usually vellum or kind style i.e. smooth to touch but lacking in sheen or glare. It may carry other furnishes, as high plate or linen. It is particularly adapted to steel-engraved wedding announcements but is frequently used for social correspondence. It is manufactured in natural shade with the basis weight range of $100\pm20g/m^2$. Generally, hand-made paper units are manufacturing this grade paper, the market for which is increasing rapidly. Hand-made wedding/greeting cards are highly expensive and mostly used by the upper class of society.

The important properties for mulberry paper:

1. It should be free from specks and shives, pin and slime holes and other blemishes, stock lumps and wrinkles. It must be of evenly finished and uniform formation.
2. It is better fibre for good paper formation to lower the long fibre cotent in the pulp. Efficient cleaning and screening are the important considerations to get a clean pulp, both for the visual appearance and because shives are web rupture causing factors.
3. Dimensional stability is important for printing grades, especially for offset papers and
4. Rosin sizing is important for writing and offset printing papers. To hard sizing may however harm the drying of offset printing inks.

Mulberry paper is a form of handmade paper. It is made from the mulberry tree and it has long fibers which help to give the paper its distinctive finish. These fibers also give mulberry paper a fine wispy edge when it is torn and this makes a very attractive finish. Mulberry paper is typically textured and is available in a variety of weights. Because mulberry paper is handmade, no two pieces are ever quite the same.

Mulberry paper can be purchased in a wide variety of sizes and weights and is readily available from craft stores, stationery supplies and art stores. In addition to selling sheets, some suppliers also sell die-cut shapes that have been cut from sheets of mulberry paper. The weights vary from thin tissue paper through to extra-thick sheets of paper. Mulberry paper is also available in a wide variety of colors. Many mulberry papers are made with other inclusions such as petals, leaves or bark. This adds to decorative finish as well as providing texture.

Uses

Mulberry paper is ideal for rubber stamping projects. While the surface of the paper is textured and therefore makes it difficult to stamp directly onto, the mulberry paper makes a wonderful background for layered projects. It is great for handmade cards and also makes an interesting addition to a scrapbook project. Not all mulberry paper is acid-free, therefore if you require the paper for a special or archival project, it is best to check with the supplier before purchasing paper.

ISSN: 3049-2289

Deckle Edges

As the mulberry paper is handmade, the sheets often have deckle edges. These are the rough edges that are formed during the papermaking process. "Deckle edged" paper can make an interesting addition to a project. Mulberry paper can be cut with a pair of sharp scissors, however, a very attractive finish can be achieved by tearing the paper. Mulberry paper tears easily, leaving a decorative wispy edge. More complex or intricate shapes can be achieved by wetting the paper where it is to be torn. The edges of the paper can be dabbed with ink to emphasize the torn finish.

Mulberry paper is ideal for adding to your rubber stamping and scrapbooking projects. It provides a rich texture that can be incorporated into your designs in a variety of ways. Use scraps of mulberry paper to add embellishments to your projects. Just cut a shape such as a heart or a flower to add to your projects as a quick way to add a feature.

Converted mulberry paper in the form of wedding or greeting cards is sent from one place to another. In India the climatic conditions vary from one part to another part of the country. Mulberry paper should have sufficient mechanical strength in order to secure the beauty of the printed wedding or greeting cards.

Therefore, mulberry should be slack sized strong writing paper characterized by good tearing and bursting strength, foldability, ruling quality, performance and durability. A good double fold value can be achieved by refining and by the use of long pliable fibres. Therefore, blending of hardwood fibres, use of optimum filler dose and required refining should be preferred for increase of smoothness. Tearing strength has particular significance in the evaluation of paper, which is subjected to tearing strains during conversion and in service. It can be achieved by use of long fibres in pulp furnish and by controlling refining of pulp.

Different types of crafting papers made from mulberry


Paper sheet made from mulberry



Different types of multicolour greeting cards made from mulberry

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Targeted breeding approaches to improve quantitative traits in cucurbits

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Introduction

Cucurbit crops belong to the family *Cucurbitaceae*, which constitute one of the most important groups of vegetable crops cultivated in tropical and subtropical regions of the world. These crops include cucumber (*Cucumis sativus*), watermelon (*Citrullus lanatus*), muskmelon (*Cucumis melo*), pumpkin (*Cucurbita spp.*), bitter gourd (*Momordica charantia*), ridge gourd (*Luffa acutangula*), bottle gourd (*Lagenaria siceraria*) and several others. They are widely grown due to their short duration, high productivity, nutritional value and adaptability to diverse climatic conditions.

Cucurbits play a significant role in ensuring nutritional security as they are rich sources of vitamins, minerals, dietary fibre, and antioxidants and possess medicinal properties such as antidiabetic and anti-inflammatory effects. Due to increasing population and changing dietary preferences, there is a growing demand for high yielding and quality cultivars of cucurbit crops.

The improvement of cucurbits mainly depends on the enhancement of quantitative traits such as yield, fruit size, earliness and stress tolerance. These traits are controlled by multiple genes and are greatly influenced by environmental conditions, making their improvement more complex compared to qualitative traits. Therefore, the adoption of suitable breeding strategies is essential for achieving sustainable improvement in these crops.

Quantitative Traits in Cucurbits

Quantitative traits are complex characters exhibiting continuous variation and are governed by multiple genes, each contributing small additive effects. These traits are typically polygenic in nature and are significantly influenced by environmental factors, resulting in a wide range of phenotypic expression. In cucurbits, important quantitative traits include vine length, number of primary branches, days to first flowering, node at first female flower appearance, fruit length, fruit diameter, average fruit weight, number of fruits per plant and total yield per plant. These traits are of major economic importance as they directly determine productivity and market value.

The genetic control of quantitative traits involves additive, dominance and epistatic gene interactions, along with significant genotype × environment (G × E) interaction. Due to this interaction, the performance of genotypes may vary across different environmental conditions, particularly for traits such as yield and earliness. Therefore, multi-environment evaluation of genotypes is essential for identifying stable and superior lines suitable for wider adaptation.

In plant breeding programmes, the assessment of genetic variability and selection efficiency is carried out using parameters such as genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), heritability and genetic advance. A high magnitude of heritability coupled with high genetic advance indicates the predominance of additive gene action, suggesting that direct selection would be effective for the improvement of such traits (Burton and DeVane, 1953).

Conventional Breeding Approaches

Selection

Selection is one of the simplest and oldest methods of plant breeding. It involves choosing superior plants from a population and propagating them for further cultivation. In cucurbits, methods such as mass selection, bulk selection and recurrent selection are commonly used.

Mass selection is easy to practice and suitable for improving traits with high heritability. However, it is less effective for complex traits like yield which are influenced by environmental factors. Recurrent selection helps in accumulating favourable genes over successive generations and is useful for improving polygenic traits.

Although selection is simple and economical, it is a slow process and requires evaluation over several generations and environments to achieve stable improvement.

Hybridization

Hybridization is an important breeding method used to create variability by crossing genetically diverse parents. It helps in combining desirable traits such as high yield, disease resistance and improved quality into a single genotype.

In cucurbits, both inter-varietal (within species) and interspecific (between species) hybridization are practiced. Interspecific hybridization is particularly useful for transferring traits such as gynoecism, cluster bearing and stress tolerance from wild or related species into cultivated varieties (Goulet *et al*., 2017).

However, hybridization may face challenges such as incompatibility, sterility and linkage drag. Therefore, careful selection and backcrossing are required to stabilize the desired traits.

Heterosis Breeding

Heterosis or hybrid vigour refers to the superior performance of F_1 hybrids compared to their parents. This method is widely used in cucurbits due to their cross pollinated nature.

Hybrids developed through heterosis breeding often exhibit higher yield, early maturity, better fruit quality and improved resistance to stresses. The success of heterosis breeding depends on the selection of genetically diverse parents with good combining ability.

Although heterosis breeding is highly effective, it requires maintenance of parental lines and production of hybrid seeds every season, which increases the cost of cultivation.

Polyploidy Breeding

Polyploidy breeding involves the induction of chromosome doubling to produce polyploid plants. This method is used to improve traits such as fruit size, vigour and seedlessness. In cucurbits, polyploidy has been successfully utilized in the development of seedless triploid watermelon. Polyploid plants often show increased cell size, thicker tissues and improved tolerance to environmental stresses (Davis *et al*., 2013). However, polyploidy breeding also has limitations such as reduced fertility and difficulty in stabilizing the plants. Therefore, it requires careful handling and evaluation.

Molecular Breeding Approaches

QTL Mapping

Quantitative trait loci (QTL) mapping is a powerful molecular approach used to identify specific genomic regions associated with quantitative traits. It involves the use of molecular markers such as SSRs and SNPs along with structured mapping populations (F_2, backcross or recombinant inbred lines) to establish associations between genotype and phenotype.

In cucurbits, QTL mapping has been widely utilized to detect genomic regions controlling important traits such as days to flowering, fruit size, fruit weight and yield. The identification of QTLs helps in understanding the genetic architecture of complex traits, including the number of loci involved, their effects and interactions. However, most quantitative traits are controlled by multiple small-effect QTLs and are influenced by environmental conditions, which may limit the consistency of QTL expression across environments (Singh *et al*., 2016).

Marker Assisted Selection

Marker assisted selection (MAS) is an advanced breeding technique in which selection is carried out using molecular markers tightly linked to desirable genes or QTLs. Unlike conventional selection, MAS enables indirect selection at the DNA level, thereby increasing the accuracy and efficiency of breeding.

It is particularly useful for traits that are difficult to measure, have low heritability, or are expressed late in the plant life cycle. It also facilitates gene pyramiding, wherein multiple desirable genes such as disease resistance and quality traits can be combined into a single genotype. In cucurbits, MAS has been successfully applied for improving traits like disease resistance, fruit quality and yield components. However, its effectiveness depends on the availability of reliable and closely linked markers (Henkrar and Udupa, 2020).

Genome Wide Association Studies

Genome wide association studies (GWAS) represent a more advanced approach for dissecting complex quantitative traits using diverse germplasm populations. Unlike QTL mapping, GWAS uses biparental populations, exploits natural genetic variation and historical recombination events to identify markertrait associations at a higher resolution.

It utilizes high-density molecular markers, particularly SNPs, across the entire genome to detect genomic regions associated with traits of interest. In cucurbits, GWAS has been increasingly used to identify genes governing yield, fruit quality and stress tolerance. This approach provides better resolution and helps in identifying candidate genes responsible for trait expression.

However, GWAS requires large and well characterized populations and is often influenced by population structure and linkage disequilibrium, which may lead to false associations. Despite these limitations, it is becoming an important tool in modern cucurbit breeding programmes (Grumet *et al*., 2021).

Conclusion

The improvement of quantitative traits in cucurbits requires the combined use of conventional and molecular breeding approaches. Conventional methods such as selection and hybridization are useful for creating variability and identifying superior genotypes. However, their efficiency is limited for complex traits that are influenced by many genes and environmental factors.

Molecular breeding approaches improve the accuracy of selection by identifying genetic regions associated with important traits. Techniques such as QTL mapping, MAS and GWAS help in early and reliable selection of desirable plants.

The integration of these approaches helps in reducing the time required for breeding and improves the efficiency of developing improved varieties. It also supports better use of available genetic resources for crop improvement.

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Genetic drain (erosion) of bajra (Pearl millet) crop and its effects on agriculture in India

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Introduction

Pearl millet (*Pennisetum glaucum* R. Br.) is a valuable crop in the semiarid and arid ecologies of Asia and Sub-Saharan Africa that are thrive very well in extreme drought conditions and poor soils (Govindraj *et al*., 2020). It is fourth important crop of India after rice, wheat and sorghum. Pearl millet is an excellent crop for the short growing season due to its capacity of high photosynthetic rate, high growth rate and short developmental stages. (Athoni *et al*., 2022). It is emerging as an important alternative crop for feed, food, fodder, and relay crop in Brazil, Canada, Mexico, United States, West Asia and North Africa region, and Central Asia (Yadav *et al*., 2021).

Tremendous progress has been made in India to improve productivity of bajra by developing high-yielding varieties including hybrids and open pollinated varieties during the last six decades (Jukanti *et al*., 2016). The accomplishments of pearl millet breeding are often referred to as one of the greatest success stories in Indian agriculture (Yadav et al., 2019). However, this progress has also responsible for genetic drain (genetic erosion) of valuable genetic resources of pearl millet. Because farmers are growing modern high yielding varieties including hybrids. Thus, genetic drain shifted farmers away from saving seeds of their traditional, open pollinated landraces season after season. The genetic drain (or genetic erosion) of the bajra crop refers to the permanent loss of genetic diversity due to development of high-yielding cultivars including hybrids. Improved cultivars in pearl millet specially hybrid varieties have increased productivity and food security but created many issues like narrowing of the genetic base in cultivated pearl millet, making it vulnerable to pests, diseases and recent challenges of malnutrition and environmental changes which are arising due to global warming.

Disadvantage of Genetic Drain in Bajra:

- **Replacement of Landraces:** Traditional landraces, which have high levels of genetic variation and adaptation to local stressors, are rapidly being replaced by improved hybrids and Open-Pollinated Varieties (OPVs). Landrace is a dynamic population of a cultivated crops that has a historical origin, distinct identity and lacks systematic scientific crop improvement, as well as often being genetically diverse, locally adapted and associated with traditional farming system (Upadhyaya *et al*., 2016). Generally, traditional farmers recognize and distinguish to landraces on basis of maturity (early, medium and late) and grain characteristics (panicle shape and length, presence of bristles, grain size and colour). Although yield is not high, the stability of named landraces in the face of adverse climatic conditions is typically higher than improved cultivars. Such named landraces developed through natural selection coupled with human selection over decades, offer a valuable gene pool for future crop improvement programmes. There are many specific examples of the contribution of pearl millet named landraces or folk varieties towards the development of modern varieties like ICTP 8203, a variety developed at ICRISAT using *Iniadi l*andrace originating in Togo. It was promising for early maturity, high seed yield,

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large seed size and downy mildew resistance and, has been released in India and Africa. Conservation and exploitation of these valuable resources along with related information is essential for use of these to overcome challenges of malnutrition and climate changes situations by develop nutrient rich and stable smart varieties in future also.

- **Narrow Genetic Base:** The widespread cultivation of a few hybrid varieties, particularly those derived from limited male-sterile lines (Tift23 A1), has created a uniform genetic background which performance may be affect due to diseases, drought heat and other unfavourable climatic conditions.
- **Downy Mildew Epidemics:** The lack of genetic diversity (specifically in the 1960s/70s) led to severe outbreaks of Downy Mildew, as pathogens easily adapted to the uniform hybrids. The pearl millets hybrids, developed by using Tift 23A1 cytoplasmic background succumbed to downy mildew infection in 1970s (Amiribehzadi A. and Satyavathi C.T., 2012).
- **Climate Change issues and increasing malnutrition problems:** Maximum modern hybrids which are developed by scientists are high yielding and increases productivity, but they may lack the diverse, wild-type stress tolerance genes required to adapt to extreme climate events (e.g., severe drought or excessive heat) as well as lack in nutrients.
- **Higher input cost for farmers:** Today maximum farmers are utilizing high yielding hybrid varieties for bajra cultivation. Farmers purchase these hybrid varietal seeds every year, because vigour or uniformity of modern hybrid varieties decline in F2 and later generations.

Efforts of maintain genetic gain (Conserving genetic diversity):

- **Preservation of germplasm:** ICRISAT and other institutes conserve over 22,000 pearl millet germplasm accessions from over 50 countries, including thousands of Indian landraces, to prevent permanent loss in Genebanks.
- **Diversification of Parental Lines:** Researchers are actively diversifying the genetic base of male-sterile lines used for hybrid production to improve resilience against diseases like Downy Mildew and other biotic and abiotic stresses. The first Pearl millet hybrid, HB-1, was released in India in 1965 (Athwal, 1965), and several promising hybrids have since been created and released for general cultivation, including HB-1, HB-2, HB-3, HB 4, and HB-5. The use of other sources of male sterility was searched and resulted in the identification of multiple alternative sources such as A1, A2, A3, A4, A5, and so on (Madane *et al*., 2021).
- **Use of Wild Relatives for development of hybrids:** Breeding programs now focus on incorporating traits from wild relatives to improve drought, salinity, and biotic stress tolerance. Burton and Athwal (1967) used A1, A2 and A3 CMS sources for developing hybrids while two other sources (Av and A4) derived from different accessions of *P. glaucum* SSP. violaceum = monodii, a wild relative of cultivated pearl millet were identified by Marchais and Pernes (1985) and a totally new and different A5 cytoplasmic male sterility system was developed by Rai (1995).

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ISSN: 3049-2289

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Modern concepts of irrigation water management

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Introduction

Water is the foundation of agricultural production and plays a critical role in maintaining food security, environmental sustainability, and rural livelihoods. Agriculture consumes the largest share of freshwater resources globally, accounting for nearly 70% of total water withdrawals. In countries like India, where agriculture is heavily dependent on monsoon rainfall and groundwater irrigation, efficient water management has become increasingly important due to declining water resources, erratic rainfall, increasing population pressure, and climate change.

Traditional irrigation methods such as uncontrolled flood irrigation are often inefficient because a significant portion of applied water is lost through evaporation, runoff, seepage, and deep percolation. These losses not only reduce irrigation efficiency but also contribute to soil degradation, nutrient leaching, waterlogging, and salinity problems. Therefore, modern irrigation concepts focus on applying water scientifically and efficiently according to crop needs while conserving water resources and maintaining environmental sustainability.

Objectives of Modern Irrigation and Water Management

1. Improving Water-Use Efficiency: The primary objective of modern irrigation systems is to maximize the efficiency of water use. Modern systems aim to reduce water losses through evaporation, runoff, and seepage.

2. Enhancing Crop Productivity: Efficient irrigation ensures that crops receive adequate moisture during critical growth stages, resulting in improved germination, nutrient uptake, photosynthesis, and ultimately higher crop yields.

3. Conserving Water Resources: Modern irrigation methods reduce excessive water application and help maintain long-term water availability.

Modern irrigation management practices:

Modern irrigation management practices are scientific approaches developed to improve water-use efficiency, crop productivity, and sustainability in agriculture. These practices help reduce water losses, improve irrigation scheduling, conserve groundwater resources, and ensure efficient utilization of available water under changing climatic conditions. With increasing pressure on water resources due to population growth, climate change, and declining groundwater levels, adoption of modern irrigation technologies has become essential for sustainable agricultural development.

1. Precision Irrigation:

Precision irrigation is an advanced scientific irrigation management approach in which irrigation water is applied precisely according to the spatial and temporal requirement of crops. It is based on the concept of site-specific water management, where variations in soil properties, crop water demand, weather conditions, and field variability are considered before irrigation application. Precision irrigation integrates technologies such as soil moisture sensors, remote sensing, Geographic Information Systems (GIS), Global Positioning Systems (GPS), drones, automated irrigation controllers, wireless sensor networks, and artificial intelligence to optimize irrigation scheduling and water application efficiency.

The main principle of precision irrigation is to maintain optimum soil moisture in the root zone while minimizing water losses through runoff, evaporation, and deep percolation. Precision irrigation helps improve water productivity by applying irrigation according to crop evapotranspiration and real-time soil moisture status. This system is particularly important under conditions of water scarcity, climate variability, and increasing pressure on groundwater resources. Precision irrigation also supports sustainable agriculture by reducing nutrient leaching, improving fertilizer-use efficiency, and minimizing environmental pollution.

Advantages:

Precision irrigation significantly improves irrigation efficiency by applying water only where and when it is required. It conserves large quantities of irrigation water, improves crop growth and productivity, reduces nutrient losses through leaching, lowers energy consumption, and enhances overall resource-use efficiency in agriculture.

2. Drip Irrigation System:

Drip irrigation is one of the most efficient micro-irrigation systems in which water is supplied directly to the root zone of plants through a network of pipes, valves, filters, and emitters under low pressure. Water is released slowly and continuously in small quantities near the plant roots, ensuring precise moisture availability and minimizing water losses. Drip irrigation is based on the principle of maintaining optimum soil moisture in the active root zone while reducing evaporation, runoff, and deep percolation losses.

Drip irrigation plays an important role in water-scarce and arid regions because of its high irrigation efficiency, which may exceed 90%. This system is highly suitable for orchards, vegetables, sugarcane, cotton, flowers, and high-value horticultural crops. Drip irrigation also facilitates fertigation, in which fertilizers are applied through irrigation water, resulting in better nutrient availability and higher nutrient-use efficiency. In modern agriculture, subsurface drip irrigation is gaining importance because it further reduces evaporation losses and improves water-use efficiency.

However, the effectiveness of drip irrigation depends on proper filtration, pressure regulation, regular maintenance, and water quality management. Poor-quality water may cause emitter clogging and uneven water distribution.

Advantages:

Drip irrigation conserves a substantial amount of irrigation water, improves nutrient-use efficiency, reduces weed growth and soil erosion, enhances crop yield and quality, and provides higher water productivity compared to conventional irrigation methods.

3. Sprinkler Irrigation System:

Sprinkler irrigation is a pressurized irrigation system in which water is applied over the soil surface in the form of artificial rainfall through nozzles and sprinkler heads. Water is pumped through a network of pipes and sprayed uniformly over crops. This method is suitable for sandy soils, undulating lands, shallow soils, and areas where land levelling is difficult.

Sprinkler irrigation operates on the principle of controlled water application at a rate lower than soil infiltration capacity to avoid runoff and waterlogging. Different types of sprinkler systems such as portable sprinklers, centre pivot systems, rain guns, and linear move systems are used according to crop type, field size, and topography. The system improves uniformity of irrigation and maintains favourable soil moisture conditions for crop growth.

Sprinkler irrigation is particularly effective for closely spaced crops, lawns, fodder crops, and vegetables. However, strong wind velocity and high temperatures may reduce application efficiency due to evaporation and wind drift losses.

Advantages:

Sprinkler irrigation ensures uniform water distribution, reduces soil erosion, improves irrigation efficiency on uneven land, conserves water compared to surface irrigation, and promotes better crop establishment and growth.

4. Smart Irrigation Systems:

Smart irrigation systems represent a modern technological advancement in irrigation management where automation, sensors, artificial intelligence, cloud computing, and Internet of Things (IoT) technologies are integrated for efficient irrigation scheduling and control. These systems continuously monitor soil moisture, crop water requirement, climatic conditions, and weather forecasts to regulate irrigation automatically.

Smart irrigation is based on real-time data collection and decision-making processes. Wireless sensor networks installed in fields measure parameters such as soil moisture, temperature, humidity, and solar radiation. Artificial intelligence and machine learning algorithms analyze this information and determine the precise irrigation requirement of crops. Farmers can remotely monitor and operate irrigation systems using mobile applications and cloud-based platforms.

The adoption of smart irrigation systems is increasing rapidly under precision agriculture because they improve water-use efficiency, reduce labor requirements, and enhance sustainability in farming systems. These systems are highly useful under climate change conditions where irrigation demand fluctuates due to varying weather patterns.

Advantages:

Smart irrigation systems improve irrigation scheduling accuracy, conserve water and energy resources, reduce labor costs, prevent over-irrigation, enhance crop productivity, and support climate-resilient agriculture through automated and data-driven water management.

5. Deficit Irrigation:

Deficit irrigation is a scientific water management strategy in which irrigation water is applied below the full crop evapotranspiration requirement during certain crop growth stages. The objective of deficit irrigation is not to maximize yield but to maximize water productivity under limited water availability conditions.

The concept of deficit irrigation is based on the principle that some crop growth stages are less sensitive to water stress than others. Controlled water deficit during these less critical stages can reduce irrigation water use without causing major yield reduction. This approach is especially important in arid and semi-arid regions where irrigation water availability is limited.

Deficit irrigation requires careful irrigation scheduling and understanding of crop physiology because excessive water stress may negatively affect photosynthesis, nutrient uptake, reproductive growth, and final crop yield. Different forms of deficit irrigation such as sustained deficit irrigation, regulated deficit irrigation, and partial root-zone drying are practiced depending on crop type and climatic conditions.

Advantages:

Deficit irrigation helps conserve irrigation water, improves water productivity, reduces irrigation costs, enhances efficient use of limited water resources, and allows cultivation of crops under water-scarce conditions.

6. Alternate Wetting and Drying (AWD):

Alternate Wetting and Drying (AWD) is an improved irrigation management technique mainly used in rice cultivation where paddy fields are alternately flooded and allowed to dry before the next irrigation. Unlike continuous flooding, AWD reduces excessive water use while maintaining crop productivity.

The technique is based on controlled irrigation scheduling in which irrigation is applied only when soil water reaches a threshold level below the soil surface. AWD improves soil aeration during drying periods, enhances root growth, and reduces anaerobic conditions in the soil. Continuous flooding in rice fields often results in large water losses and methane emissions. AWD addresses these problems by improving water-use efficiency and reducing greenhouse gas emissions.

AWD is recognized as an important climate-smart water management practice because it conserves water and contributes to environmental sustainability. However, improper drying during sensitive growth stages may reduce rice yield if not managed properly.

Advantages:

AWD significantly reduces irrigation water use, lowers methane emission from rice fields, decreases irrigation cost, improves root development, enhances water productivity, and supports sustainable rice cultivation.

7. Climate-Smart Water Management:

Climate-smart water management is an integrated approach that combines efficient irrigation technologies with climate adaptation and mitigation strategies to improve agricultural resilience under changing climatic conditions. This concept emphasizes sustainable use of water resources while increasing crop productivity and reducing environmental impact.

Climate-smart water management includes practices such as mulching, conservation agriculture, rainwater harvesting, crop diversification, drought-tolerant crop varieties, precision irrigation, and efficient irrigation scheduling. Mulching reduces soil evaporation and conserves moisture, while conservation agriculture improves soil structure, infiltration, and water-holding capacity. Weather forecasting and climate information services also help farmers plan irrigation according to anticipated rainfall and temperature conditions.

This approach is highly important because climate change is increasing the frequency of droughts, floods, heat stress, and irregular rainfall patterns, which directly affect agricultural water availability and crop productivity.

Advantages:

Climate-smart water management improves water conservation, enhances resilience against drought and climate stress, maintains sustainable crop production, reduces environmental degradation, and supports long-term agricultural sustainability under climate change conditions.

8. Remote Sensing and GIS Applications

Remote sensing and Geographic Information System (GIS) technologies are modern tools widely used in irrigation planning, crop water stress assessment, soil moisture monitoring, drought forecasting, watershed management, and water resource planning. Remote sensing uses satellite imagery, drones, and aerial photography to collect information regarding crop conditions and field variability without direct physical contact.

GIS integrates spatial and non-spatial data for analyzing irrigation requirements, water distribution, and resource management. Thermal and multispectral satellite images help identify crop water stress and irrigation needs at different growth stages. These technologies are increasingly used under precision agriculture for large-scale irrigation management and decision-making. Remote sensing and GIS also support policymakers and agricultural planners in monitoring groundwater depletion, reservoir levels, and drought conditions.

Advantages:

Remote sensing and GIS provide accurate and real-time information for irrigation planning, improve water resource management, help detect drought and crop stress early, support precision agriculture, and enable efficient monitoring of large agricultural areas.

9. Integrated Water Resource Management (IWRM):

Integrated Water Resource Management (IWRM) is a holistic and multidisciplinary approach for coordinated management of water, land, and environmental resources to maximize economic and social welfare without compromising ecological sustainability. IWRM recognizes that water resources are interconnected with agricultural production, environmental conservation, industrial development, and social well-being.

The main principle of IWRM is the integrated and participatory management of water resources at watershed, regional, and national levels. It involves coordination among farmers, policymakers, industries, local communities, and environmental agencies for efficient allocation and sustainable utilization of water resources.

IWRM emphasizes conjunctive use of surface water and groundwater, rainwater harvesting, watershed development, pollution control, and equitable distribution of water among users. This approach is highly important for addressing challenges such as groundwater depletion, water conflicts, environmental degradation, and increasing water demand.

Advantages:

Integrated water resource management promotes sustainable utilization of water resources, improves coordination among water users, reduces water conflicts, enhances groundwater conservation, protects environmental quality, and ensures long-term water security for agriculture and society.

Challenges in Adoption of Modern Irrigation Systems:

High Installation Cost:

Modern irrigation systems such as drip and sprinkler irrigation require high initial investment for pipes, pumps, filters, sensors, and automation equipment. Small and marginal farmers often cannot afford these technologies because of limited financial resources and poor access to credit facilities. The high installation and maintenance cost reduces large-scale adoption of advanced irrigation systems.

Lack of Technical Knowledge:

Modern irrigation technologies require proper technical knowledge for installation, operation, irrigation scheduling, and maintenance. Many farmers are unaware of the scientific management practices associated with these systems. Lack of training, extension services, and technical support often leads to improper use and reduced efficiency of irrigation systems.

Energy Constraints:

Most modern irrigation systems depend on electricity, diesel, or solar energy for operating pumps and irrigation networks. In many rural areas, irregular electricity supply, power shortages, and high fuel costs affect efficient irrigation management. Energy scarcity increases irrigation cost and limits the effective operation of automated irrigation systems.

Small Land Holdings:

Small and fragmented land holdings make the installation of modern irrigation systems difficult and less economical. Farmers with small fields often hesitate to invest in expensive irrigation infrastructure because of low economic return. Fragmented fields also create problems in pipeline layout, water distribution, and irrigation management.

Conclusion:

Modern concepts in irrigation and water management are essential for sustainable agricultural development under increasing water scarcity and climate variability. Advanced irrigation systems such as precision irrigation, drip irrigation, sprinkler irrigation, smart irrigation, AWD, and fertigation significantly improve water-use efficiency and crop productivity while conserving natural resources.

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Natural Farming for Sustainable Agriculture

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Natural farming is an indigenous farming method based on indigenous cow and cow urine. In this farming method there is no chemical fertilizers, pesticides and less financial involved in it. All the input items used in the natural farming are natural resources and home made only. In the Indian context, natural farming is a local low-input climate-resilient farming system that advocates the complete elimination of synthetic chemical agro-inputs. Instead, it encourages farmers to use low-cost, locally sourced inputs such as natural mixtures made using cow dung, cow urine, jaggery, pulse flour, mulch, crop covers, and symbiotic intercropping to stimulate the soil's microbial activities. Natural farming is a broader term which not only covers agro-ecological science but involves the other transdisciplinary fields encompassing socio-cultural, technological, economic and political dimensions of food systems from production to consumption. The natural farming is gaining momentum in India and is being practiced over 6.50 lakh hectares of agricultural land in 11 states of the country (NITI Aayog). It involves all aspects of living harmony with nature based on the foundation of agroecological principles in context to setting up the universal sustainable food systems and healthy life.

Natural Farming emphasize on use of chemical free practices and easily available farm resources which are manageable for better economy and conservation of nature in long term which helps to ease smallholder farmers in reducing the dependency on purchased inputs. The important aspects of natural farming it is considered as a cost- effective farming suitable for livelihood of large number of farmers and rural development. The top states encouraging natural farming are Andhra Pradesh, Himachal Pradesh, and Gujarat. Other States like Uttar Pradesh, Madhya Pradesh, Odisha, Chhattisgarh, Himachal Pradesh, Jharkhand and Tamil Nadu are also practicing this type of farming (Figure 1). Central government launched a natural farming promotion scheme during 2020-21; Bharatiya Prakritik Krishi Paddhati (BPKP) a sub scheme under PKVY. Nearly 6.1 lakh ha has been covered in above said states with total fund of 49.8 crore. There are many opportunities for starting natural farming in our nation because of the varied agro-climates and the richness of farmers' traditional knowledge (Kumar et al., 2019).

Natural Farming is of utmost importance for conservation of beneficial soil microorganism, conservation of soil fertility,protection of environment, reduction of cultivation cost, protection of Human Health ,increasing water holding capacity in soil, preventing soil erosion, increasing overall income and non usage of chemical pesticide and fertilizer. Natural farming system is diversified farming system that integrates crops, weeds, grasses, forest trees and Livestock allowing optimum use of functional biodiversity. Natural farming practices based on ecological principles and laws of nature are being advocated by United Nation to promote sustainable food systems to enhance food and nutrition security. Under the alarming risk of climate change on agriculture, the practices of natural farming are the need of hour for sustainable agriculture and creating the green economy. India

ISSN: 3049-2289

having the diverse agroclimatic conditions have many niche areas where natural farming principles can play a vital role to promote sustainable livelihood and reduce the risk of high input agriculture under given agro-climatic conditions and unpredictable shift in market based management of basic amenities of life.

Basic universal principles of Natural Farming

a. Co - existence in Natural Farming: It is the state or fact of living or existing at the same time or in the same place. Coexistence is defined as a dynamic but sustainable state in which humans and wildlife co-adapt to living in shared ecosystem, landscapes, where human interactions with wildlife are governed by effective institutions that ensure long-term wildlife population persistence, social legitimacy, and tolerable levels of risk .

b. Principal of Complementary: It is the quality of being different but useful when combined form strongest matches. Every living organism complements each other in nature to keep balance of nature intact.

c. Principal of Diversity: It is the variations in ecosystems within a geographical location and its overall impact on human existence and the environment. Ecosystem diversity addresses the combined characteristics of biotic properties and abiotic properties.

d. Principal of crop density: It is the principle which deals with number of crop, plants, species that occurs within a farm unit. Number of plants per unit area in the cropped field is the plant population or plant density.

e. Principal of Ecology: It is the principle that deals with relationships between living organisms, including humans, and their physical environment; it seeks to understand the vital connections between plants and animals and the world around them. The other important principles are ploughing, water management, crop direction, intercropping and mulching.

Aims and Objectives for Natural Farming promotion:

- Preserve natural flora and fauna
- Restore soil health and fertility and soil's biological life
- Maintain diversity in crop production
- Efficient utilization of land and natural resources(light, air, water) • Promote natural beneficial insects, animals and microbes in soil for nutrient recycling and biological control of pests and diseases
- Promotion of local breeds for livestock integration
- Use of natural / local resource-based inputs
- Maintain healthy, nutritional agricultural produce for consumption
- Reduce input cost of agricultural production
- Improve economics of farmers

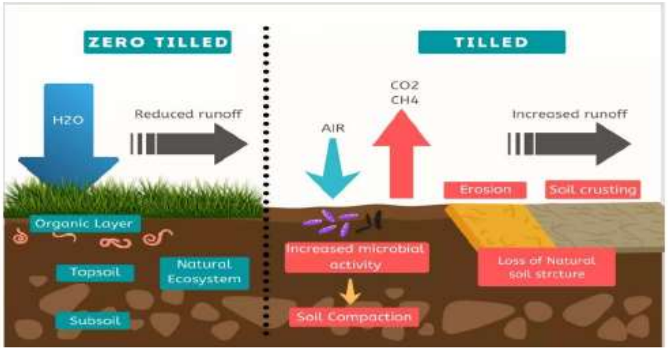
Natural farming Practices

Natural farming aims at restoring soil health, maintenance of diversity, ensure animal welfare, stress on efficient use of natural/local resources and promote ecological fairness. It is an ecological farming approach where farming system works with the natural biodiversity, encouraging the soil's biological activity and managing the complexity of living organisms both plant and animal to thrive along with food production system. Farming practices essential for adoption of natural farming includes:

- No external inputs
- Localseeds (use of local varieties)
- On-farm produced microbial formulation forseed treatment (such as Beejamrita)
- On-farm made microbial inoculants (Jivamrita) for soil enrichment
- Cover crops and mulching with green and dry organic matter for nutrient recycling and for creating a suitable micro-climate for maximum beneficial microbial activity in soil.
- Mixed cropping

ISSN: 3049-2289

- Managing diversity on farm through integration of trees
- Management of peststhrough diversity and local on-farm made botanical concoctions(such as Neemastra, Agniastra, neem ark, Dashparni ark etc)
- Integration of livestock, especially of native breed for cow dung and cow urine as essential inputs for several practices and water and moisture conservation.



Four main pillars of zero budget Natural Farming

In natural farming it is expected that the nutrient required for the plant growth is available in the soil. If we allow the microbial cycles to operate as in natural ecosystem it will take care of the nutrient requirement of plants. The only thing the farmer is expected to do is to add as much quantity of organic matter, that too from the same farm land, back to soil. Even composting need not be attempted by the farmers. On the soil surface the organic matter has to decompose gradually over a period of time. For the successful natural farming there are four main components (pillars) are proposed and are as follows. 1) Bijamrita / beejamrutha for seed treatment 2) Jivamrita / jeevamrutha to supply of nutrient to plants through enhanced microbial activity 3) Acchadana - mulching - crop residue management for weeds, nutrients and water 4) Whapasa - soil aeration and moisture conservation.

1. **Preparation of Bijamrita**

The composition includes 20 liters of water, 5 kg of cow dung, 5 liters of cow urine, 50 g of lime, and a handful of soil.

1. In a plastic or cement tank, mix all the ingredients. Stir the mixture with a wooden stick, rotating it clockwise to infuse positive energy.

2. Cover the tank with a jute sack or poly net, ensuring it's positioned in a shaded area, shielded from direct sunlight and rain.

3. After a day, the beejamrutha will be ready for seed treatment. Preparation Time: 12-24 hours

Storage: Use the beejamrutha for seed disinfection. It can be stored for up to 7 days.

2. Jeevamrut, an organic fertilizer, containing beneficial microorganisms that convert essential nutrients to a usable form when added to the soil. It can be sprayed or added to irrigation every 10-15 days until the soil improves. Jeevamrutha is an organic alternative to chemical fertilizers, rich in nutrients like carbon, nitrogen, phosphorus, and calcium. It boosts soil microorganisms, enhancing soil fertility and crop yield. It's made from cow dung and urine, promoting nutrient availability and microbial activity. This leads to more earthworms and fertile soil. Jeevamrutha is a bio-fertilizer that enhances plant growth by stimulating soil microbes and earthworms. It includes important microorganisms like rhizobacteria, cyanobacteria, mycorrhizal fungi, and nitrogen-fixing bacteria. This product catalyzes nutrient conversion and helps fight plant diseases. Subash Palekar recommends Jeevamrutha for nutrient conversion in plant roots. It contains PGPR, cyanobacteria, Solubilizing Bacteria (PSB), mycorrhizal fungi, and Nitrogenfixing bacteria, aiding nutrient absorption and disease control. It's effective for the first 3 years, after which the system stabilizes. Soil microorganisms actively impact fertility by cycling nutrients like carbon and nitrogen essential for plant growth. Jeevamrutha is a fermented culture that not only provides nutrients but also stimulates microbial activity and earthworms. It's beneficial against fungal and bacterial diseases. According to Palekar, it's necessary for the initial 3

ISSN: 3049-2289

years of transition to a self-sustaining system. Types of jeevamrutham

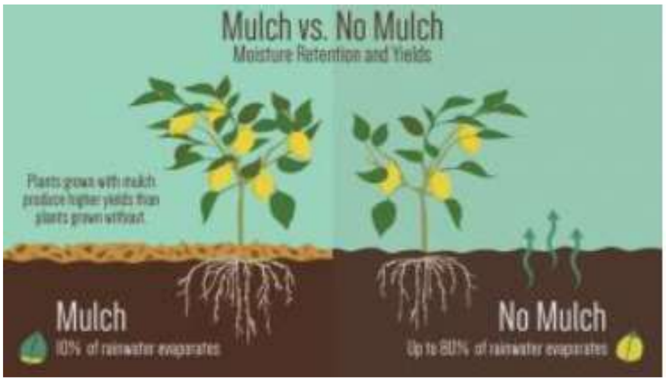
1) The liquid state of Jeevamrutham.

2) The semi-solid state of Jeevamrutham.

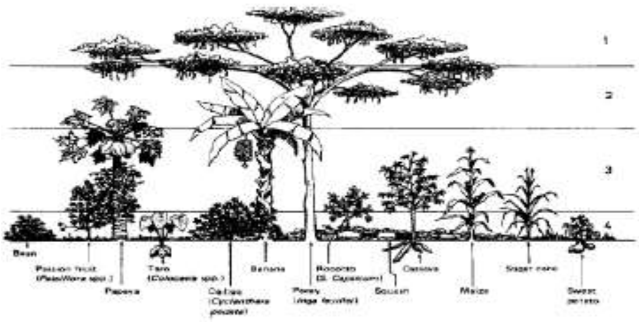
3) Dry Jeevamrutham (Ghana jeevamrutham).

Preparation: To make jeevamrutha, follow these steps: Fill a barrel with 200 liters of water. Add 10 kg of fresh local cow dung and 5 to 10 liters of aged cow urine. Include 2 kg of natural jaggery, 2 kg of pulse flour, and a handful of soil from the farm's bund. Mix the solution thoroughly and let it ferment for 48 hours in the shade. which is ready to be applied. For one acre of land, 200 litres of jeevamrutha is sufficient. Apply it to the crops twice a month either through irrigation water or as a 10% foliar spray. This process should continue every 15 days until the soil is enriched. During the 48-hour fermentation process, aerobic and anaerobic bacteria in the cow dung and urine multiply as they consume organic ingredients, including pulse flour. Adding a handful of undisturbed soil serves as an inoculate of native microbes and organisms to the mixture.

3. Acchadana/Mulching Grain crops and healthy orchard trees thrive with a ground cover of vegetables, weeds, and white clover. Mulching with straw enhances soil moisture and encourages microorganisms and earthworms, fostering seed germination without tillage. There are three mulching types: a. Soil mulch: Protects topsoil during cultivation, promoting aeration and water retention within the upper 4.5 to 6 inches (10-15 cm) layer. Avoid deep ploughing as recommended in Natural farming. b. Straw mulch: Comprising dried biomass waste or any dead organic material, it contributes to soil fertility by decomposing through microbial activity. c. Live mulch (Symbiotic Intercrops and Mixed Crops): Diverse cropping patterns supply essential elements to soil and crops. Cover crops like legumes reduce weeds, enhance water infiltration, and fix atmospheric nitrogen for crops. Surface residues increase microbial degradation and nutrient release. It conserves soil moisture, improves seed germination, and regulates soil temperature. Under natural farming, soil mulching, straw mulching, and live mulching offer numerous benefits: *viz.*, reduces Tillage, enhances biological activity and reinvigorates soil nutrient content.



Mulching



Multi storied cropping system

4. Whapasa/Moisture refers to a soil condition with a balanced mixture of 50% air and 50% water vapour between soil particles. This state reduces irrigation needs and is a foundational concept of natural farming. In this approach, where both air and water molecules are present in the soil, water application is reduced, primarily irrigating at noon in alternate furrows. This technique enhances water use efficiency and has led to decreased irrigation demands among the natural farming farmers. In natural farming, water conservation and precise water application based on crop requirements are paramount. By focusing on irrigation during noon in alternate furrows, the goal is to maintain a balance of air and water molecules in the soil. This practice capitalizes on the fact that younger, more active roots

ISSN: 3049-2289

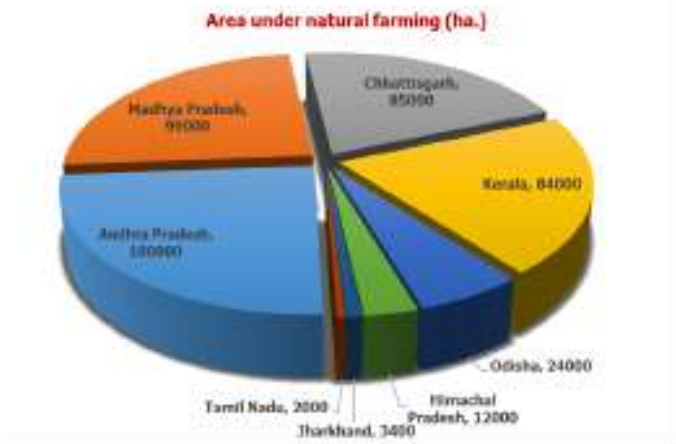
absorb water and nutrients more effectively. It's crucial to strike a balance, as excessive water can limit soil aeration and lead to oxygen deficiency, potentially harming plants. Soil aeration is vital for plant growth, so longer intervals between water applications are advisable. It optimizes water use and foster healthier plant growth while conserving water resources.

Jeevamrith preparation

Intercropping of wheat & chickpea on bed and furrow

In India, natural farming is actively championed to promote sustainable development. Initiatives like the National Mission on Natural Farming and state-led models like the Andhra Pradesh Community Managed Natural Farming (APCNF) provide training, resources, and community networks to help farmers transition safely and successfully. Current scenario of Natural Farming in India Natural farming is gaining popularity in India. As of 2023, it is estimated that about 4.09 lakh hectares of land in India (Figure 2) are under natural farming and total fund of Rs. 4587.17 lakh has been released in 8 States across the country including the State of Tamil Nadu. The leading states in terms of area under natural farming through the scheme BPKP:

Fig 1: Prominent states practicing Natural farming in India



- ♣ Andhra Pradesh (1.00 lakh hectares)
- ♣ Madhya Pradesh (0.99 lakh hectares)
- ♣ Chhattisgarh (0.85 lakh hectares)
- ♣ Kerala (0.84 lakh hectares)
- ♣ Odisha (0.24 lakh hectares)
- ♣ Himachal Pradesh (0.12 lakh hectares)
- ♣ Jharkhand (0.034 lakh hectares)
- ♣ Tamil Nadu (0.02 lakh hectares)

Among the various models of natural farming, the zero-budget natural farming (ZBNF)and Andhra Pradesh Community based Natural Farming (APCNF) models are widely used in India. As per the report of Niti Aayog, India can double the acreage of chemical-free farming to 15% immediately and grow it to 30% by 2030. The report says that this practice

ISSN: 3049-2289

would not hurt national food security as the resultant loss in output and exports would be compensated by the reduction in fertiliser subsidies. The National Institute of Agricultural Extension Management (MANAGE), Hyderabad is the Nodal agency for promotion of natural farming in the country. The agency creates a large pool of natural farming experts through conduct of several capacity building programmes to the officials from different Central and State level institutes/ Departments of agriculture, SAUs, private sector organisations and also through various awareness campaigns to the farmers across the country. The Government of India has also launched a National Mission on Natural Farming (NMNF) during 2023 with the aim of motivating farmers to adopt chemical free farming and to enhance the reach of natural farming in the country.

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Strategies to Enhance Potassium Uptake in Crops

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Introduction

Potassium (K) is a vital nutrient for crop growth, playing a central role in various physiological processes that affect plant health and productivity. Efficient potassium management is essential to maximize crop yields while minimizing environmental impacts. Potassium (K) is an essential nutrient for plants, accounting for about 5% of their dry biomass. Although it is not a structural component, it plays a crucial role in many physiological processes, including protein and starch synthesis, osmotic regulation, turgor maintenance, cell expansion, membrane potential regulation, and pH balance. It also activates over 60 enzymes. Adequate potassium improves crop quality and strengthens a plant's resistance to both biotic and abiotic stresses. Some plants can absorb potassium in amounts greater than required for normal growth, a phenomenon known as "luxury consumption." This excess uptake may serve as an insurance mechanism, helping plants withstand sudden environmental stresses.

Deficiency Symptoms: Potassium (K) is mobile within plants; deficiency symptoms first appear in older leaves. A lack of K disrupts normal metabolic activities, leading to reduced growth and productivity. In severe cases, the scorched ("fired") margins may dry out, break off, and the damage can extend toward the midrib.

- Leaf Marginal Chlorosis and Necrosis
- Curling and Drooping Leaves
- Interveinal Chlorosis and necrosis along the leaf margins, starting from the lower, older leaves.
- Purple or Bronze Spots
- Poor Flowering and Fruit Development
- Plants deficient in potassium are generally weak and poorly developed.
- Seeds become shrivelled, while fruits and vegetables often fail to develop normal colour, resulting in poor quality, reduced storage life, and shorter shelf life.

Figure 2. Deficiency symptoms of K in plant

Potassium (K) Dynamics in Soil

Potassium is the eighth most abundant element, constituting about 2.5% of the earth's crust. Plants acquire K^+ only from the soil solution through root epidermal and cortical cells. In soil, K exist in four principal forms: ionic form in soil solution (0.1-0.2%), exchangeable K (1-2%), fixed or non-exchangeable K (1-10%), and lattice K (90-98%) (Sparks, 1987). All these forms are dynamic in nature (Figure 2). Lattice K consist of K bearing minerals such as feldspars (orthoclase and plagioclase) and phyllosilicates (micas, chlorite, etc.) which release

K+ in the course of their weathering. Solution K and exchangeable K are considered to be labile and are in dynamic equilibrium to meet the immediate requirements of growing plants, while the latter two forms are considered non-labile K and are responsible for the long-term supply of K to plants.

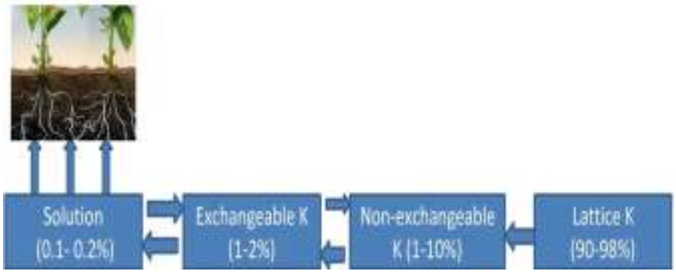

Figure 2. Dynamic equilibrium of different forms of K in soil

Losses of K from Soil

Potassium (K) losses comprise of removals in harvested crops and losses via leaching, water erosion and wind erosion. Crop Removal: Modern intensive agriculture leads to significant removal of K from the soil through harvested portion and this constitutes the largest loss of potassium from soil. The total quantity of K lost increased with rise in total K accumulation (uptake) and crop productivity.

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Modern intensive agriculture leads to significant removal of K from the soil through harvested portion and this constitutes the largest loss of potassium from soil. The total quantity of K lost increased with rise in total K accumulation (uptake) and crop productivity.

Water Erosion: According to ICAR-IISWC, water erosion affects 73.3 m ha of our arable land, and this adversely affects agricultural production, water quality, soil fertility, hydrology and environmental sustainability. Water erosion removes the top fertile soil highly concentrated with crop nutrients through surface run-off, drainage water and sediments.

Wind Erosion: Abrasion, burial, dust deposition, etc. during wind erosion damaged crops. Apart from this, detachment of nutrient rich top soil particles removes soil organic matter and nutrients along with it. These soil particles contain a significant portion of the bulk soil's K supply.

Leaching: As K+ is a mobile ion, it can move along with the drained water down the soil profile. Consequently, significant amounts of K can be leached below the rhizosphere volume by percolating water. The quantity of K leached from the soil is a function of soil texture, soil pH, cation exchange capacity, water regime and available K. Sandy soil, soils with low cation exchange capacity, higher the water depth, higher soil available K and larger K rates increased K leaching.

Strategy for Use Potassium Fertilizer for Increasing Potassium Use Efficiency Increasing potassium (K) use efficiency through effective potassium fertilizer management is crucial for optimizing crop yields, minimizing input costs, and reducing environmental impacts. Here's a strategy for using potassium fertilizer to enhance K use efficiency:

Synchrony of K Supply with Plant Demand:

In most annual crops, basal application of the full dose of K fertilizer is a common practice. However, this is often not suited to supply adequate K to the crops during peak demand phases. The timing of K fertilizer application to crops is site and crop specific.

Crop-Specific Recommendations: Refer to crop-specific nutrient management guidelines or recommendations provided by agricultural extension services or experts to determine the potassium requirements for the crops you plan to grow. Adjust potassium fertilizer rates based on the specific needs of each crop.

Balanced Fertilization: Application of nutrients in optimum rates and adequate amount is necessary for higher KUE. Excess application is wasteful, while inadequate application could not meet plant nutrient demands, and both these processes detrimental for achieving higher production and productivity.

ISSN: 3049-2289

Balanced supply of essential nutrients is necessary to maintain higher KUE.

Integrated Plant Nutrient System: IPNS enhances crop and soil productivity, maintain soil fertility and improve farm profitability through balanced use of chemical and organic fertilizers along with biological sources of plant nutrients. Use of FYM, biofertilizers, green manure and short duration legumes could substitute up to 25-50% of crop K needs.

Crop Residue Management: As crop residues usually contain more K (>80%) than the harvested seed, it can partially substitute a portion of crop fertilizer requirement and augment soil K content. Residue incorporation reportedly ameliorates the negative K balance and improved soil water-soluble, exchangeable, and non-exchangeable K.

Placement Techniques: Consider placement techniques that enhance potassium uptake. For example: Banding or placing potassium fertilizer in proximity to the root zone can improve nutrient availability to plants. Split applications throughout the growing season can also enhance K uptake.

Crop Specific Potassium Requirements

Crop-specific potassium (K) requirements are essential considerations in agricultural nutrient management. Different crops have varying K needs at different growth stages.

1. Cereals (e.g., Wheat, Rice, Corn)

- Cereals generally require substantial potassium throughout their growth cycle.
- Adequate potassium promotes grain filling, root development, and resistance to lodging (stem bending or breaking).
- Potassium deficiencies can result in reduced yields and poor grain quality.

2. Legumes (e.g., Soybeans, Peas)

- Legumes often have moderate potassium requirements.
- Potassium supports nitrogen fixation in legume nodules and overall plant growth.
- Maintaining potassium levels is crucial for optimal nitrogen fixation.

3. Fruits and Vegetables

- Potassium is vital for fruit development, quality, and flavor in fruits and vegetables
- Adequate potassium during the reproductive stage ensures the production of larger, tastier fruits and vegetables.

4. Root Crops (e.g., Potatoes, Carrots)

- Root crops require potassium for tuber or root development.
- Adequate potassium promotes healthy root growth and higher yields.

5. Oilseeds (e.g., Canola, Sunflower)

- Oilseeds generally have moderate to high potassium requirements.
- Potassium is essential for oilseed development and oil production.
- Deficiencies can lead to reduced oil content in seeds.

Crop-specific potassium requirements can vary depending on factors such as soil type, climate, and local nutrient availability. Soil testing is a valuable tool for determining the specific potassium needs of crops in a particular field. Soil test results, along with knowledge of crop requirements, can guide potassium fertilizer recommendations to ensure that crops receive the appropriate levels of this essential nutrient at different growth stages.

Conclusion

Efficient potassium management is essential for sustainable agriculture. By following soil testing, crop-specific recommendations, balanced fertilization, proper timing, and precision techniques, farmers can enhance potassium use efficiency, optimize crop yields, and reduce

ISSN: 3049-2289

environmental impacts. There is no doubt about the importance of K fertilization for achieving food security of the country. Given that all K fertilizers are imported, all efforts must be made to improve the KUE, use other alternative sources and reducing the various pathways of losses.

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Artificial Intelligence in Agricultural Extension

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The increase of the global population, which is expected to achieve 10 billion by 2050, is giving excessive pressure on the agricultural sector to raise crop production as well as increase yields. To address future food shortages, there may be two potential approaches have developed like developing land use and using large-scale farming, or implementation of innovative practices to increase productivity on prevailing farmland.

Artificial Intelligence (AI) is quickly emerging as a transformative force in agriculture. AI provide a solution by giving data-driven support to farmers and extension services. It empower precision farming through technologies like crop yields, drones, optimizing resource utilization and sensors.

For decades, agricultural extension services have functioned as a key mechanism for supporting farmers through the dissemination of improved practices, technologies, and innovations developed by agricultural research institutions (Joel *et* al., 2025). In agriculture, AI applications including machine learning, computer vision for pest and disease detection and natural language processing tools that assist personalized farmer communication (Kamilaris and Prenafeta- Boldú, 2018; Liakos, Busato, Moshou, Pearson and Bochtis, 2018). Farming is a high-priority field, with about 30.7 percent of the world's population dedicated to 2781 million hectares of agricultural land (Dutta, *et al*., 2020). AI, incorporating automation, machine learning and data analytics can extensively boost the efficiency of agricultural extension by connecting the power of data, intelligent systems and algorithms (Smith *et al*.,2020)

In developing country, traditional agricultural extension systems perform as a critical source of assistance for farmers. The number of this systems is inadequate as compared to the huge population of smallholder farmers. Lowder *et al*.(2016) reported that small and family farms, estimated to be at least 570 million in number and are cultivated by more than 1 billion individuals involved in agriculture, including over 28 percent of the global workforce (Cassidy and Snyder, 2019). Crop yields are extensively impacted by damage caused by disease and pest as well as nutrient insufficiencies which results in probable losses of up to 30 percent. This emphasised the need for widespread dissemination of agricultural technology and support. Furthermore, there is a demand for comprehensive and timely information concerning innovative farming techniques, as well as the correct utilization of pesticides and fertilizers (Kumar *et. al*., 2020). Dwindling irrigation water supplies, climate change, rising production costs and a decline in the farm workforce have all wreaked havoc on agriculture production systems during the previous few decades (Jung *et al*., 2021). AI-powered predictive models assist predicts contributing to sustainability, pest outbreaks, optimize crop management and make better use of scarce resources, (Jha *et al*.,2019). AI-driven technologies have reformed precision agriculture by assisting more detailed and effective resource management. Smith *et al.* (2019) revealed that AI-driven precision agriculture tools, like remote sensing as well as data analytics, have enriched resource optimization, crop monitoring and yield prediction.

ISSN: 3049-2289

What is Artificial Intelligence (AI)?

Abbreviation of AI is Artificial Intelligence which refers a capacity of machine which implement cognitive functions associated with human thought processes. It is a branch of computer science which focuse in developing and overseeing technology which are capable of freely learning, taking decisions, and executing actions on behalf of humans.

However, AI basically refers to machines which react to stimuli in a way stable with human responses, taking into account human capabilities for observation, judgment, and intention. These kind of softwares have the ability to take decisions demanding a level of know-how comparable to that of humans, helping individuals in predicting problems or focusing issues as they arise. AI is a multidisciplinary field of study offered to ceating computers and machines capable of learning, reasoning and acting in ways that usually need human intelligence or include data at a scale beyond human analytical proficiencies. AI incorporates a wide range of disciplines, including statistics, linguistics, computer science, data analysis and hardware and software engineering, neuroscience and even psychology and philosophy.

How AI works in general?

AI systems works by managing huge sets of training data and examining the data for patterns, connections and leveraging these patterns to make predictions about forth coming occurrences. However, a chatbot uncovered to text examples get the capability to create natural-sounding discussions with individuals, while an image identification tool can develop the ability to recognise and describe objects within images after assessing millions of illustrative instances.

AI programming centers around cognitive capabilities that incorporate the following:

1. Self-correction: This feature of AI programming is converted to continuously refine algorithms, confirming that they provide the most detailed results as much as possible.
2. Learning: This feature of AI programming centers on the attainment of data and the construction of rules for transforming it into actionable information. These rules, referred to as algorithms, furnish computing devices with precise, step-by-step instructions for accomplishing specific tasks.
3. Reasoning: AI programming focuses on choosing the right algorithm to get a required result.
4. Creativity: This dimension of AI connects statistical methodologies, neural networks, rules-based systems and different other AI system to create new music, new concepts, images and text.

Types of artificial intelligence

Artificial intelligence can be divided in different ways, based on its developmental stages or performance. There are commonly four stages of AI development:

1. **Reactive machines:** This include AI systems which respond to various stimuli based on pre-programmed rules. They lack memory and the capability to understand from new data.
2. **Limited memory:** Presently most of the AI falls under the limited memory. These kind of systems can use memory to increase over time through training with new data or same training models.
3. **Theory of mind:** Present research discovers the concept of theory of mind AI. This type of AI would be able of following the human mind and take decisions with humans, involving diagnosing and remembering emotions and react in social situations as humans do.
4. **Self-aware:** Self-aware AI refers to a hypothetical machine that retain self-awareness, intellectual capabilities, and emotional understanding akin to those of a human. Similar

ISSN: 3049-2289

to theory of mind AI, self-aware AI does not presently exist.

Artificial Intelligence in agricultural extension

Artificial Intelligence (AI) is making extensive progress in the field of agricultural extension, reforming the speadinf of information, decision-making processes, and the improvement of farming techniques. Here are key features of AI's role in agricultural extension:

1. **Language processing:** Natural language processing (NLP) AI models can transform agricultural matter into local languages, enhancing the accessibility of extension services to a bigger spectrum of farmers, specially in regions with various linguistic backgrounds.

2. **Precision farming:** AI-driven technologies like sensors, drones and satellite imaging are engages for real-time data collection referring to crop health, soil conditions, weather patterns and more. This data is consequently analyzed to provide farmers with detailed suggestions regarding fertilization, planting, pest control and irrigation. Precision farming operates to improve resource utilization and increase crop yields.

3. **Data analytics:** AI algorithms process huge dimension of agricultural data, supporting extension services and farmers in taking data-driven decisions. This involves estimating disease epidemics, improving planting lists as well as taking proper crop varieties for certain regions.

4. **Crop surveillance:** AI-driven image identification and computer vision systems assist automated monitoring of crops. These systems can detect pest and diseases, nutrient insufficiencies in crops through analysis of image, releasing timely signals and suggestions to moderate these issues and reduce crop losses.

5. **Market analysis:** AI tools analyze prices of commodity, market data and demand trends, encouraging farmers to make choices about crop selection and timing for optimum profit making.

6. **Chatbots and virtual assistants:** AI-powered chatbots and virtual assistants are arranged to give farmers with immediate approach to information and guidance. Farmers can take advice on agricultural practices like weather forecasts, market prices etc.

7. **Support for extension workers:** AI tools helps extension workers by providing them with related information, suggesting best practices, and assisting in prioritizing interactions with farmers.

8. **Climate adaptation:** AI models support farmers in adjusting to climate change by providing awareness into climate trends, suggesting resilient crop varieties, and optimum utilization of water.

9. **Farm management systems:** AI-based farm management platforms combine data from different sources, including IoT sensors, weather stations and historical records. It helps to monitor utilization of resources, various farm operations etc.

10. **Training and education:** E-learning platforms offers personalized training modules as well as resources to farmers, facilitating them to get new skills and stay updated on the present agricultural practices.

Benefits of AI in Agricultural Extension

1. **Increased Efficiency :**AI provides information immediately and correctly to many farmers simultaneously.

2. **Personalized suggestions:** suggestions can be made according to:
   - Climate
   - Crop condition
   - Farm size
   - Soil type

ISSN: 3049-2289

3. **Cost Reduction:** AI reduces excessive use of:
    - Pesticides
    - Water
    - Labor
    - Fertilizers
4. **Improved Decision-Making:** It help farmers to take better farming decisions.
5. **Wider Reach:** Digital platforms can reach remote and rural areas.

Challenges of AI in Agricultural Extension

1. **Digital Illiteracy:** Most of the farmers may have shortage of technical skills to apply AI tools.
2. **Poor Internet Connectivity:** Weak digital infrastructure often create problems to access.
3. **High Initial Costs:** AI technologies and smart devices may be costly for small and marginal farmers.
4. **Data Privacy Issues:** Assemble and utilisation of farmers' data increase privacy concerns.
5. **Language and Localization Problems:** AI systems may not promote all regional languages as well as local farming situations.

Role of Extension Workers in the AI Era

AI enhance extension workers' effectiveness without replacing them. Extension professionals will:

- Train farmers to use digital tools.
- Interpret AI recommendations
- Provide field-level guidance
- Bridge the gap between technology and rural communities
- Build farmer trust

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Nano-fertilizers: Climate-Smart Fertilizers for Higher Nutrient Use Efficiency and Productivity

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Introduction

Global agriculture faces dual challenge of ensuring food security for a rapidly growing population while simultaneously reducing the environmental footprint of farming systems. For decades, this challenge has been addressed largely through increased application of synthetic fertilizers. However, the nutrient use efficiency (NUE) of conventional fertilizers remains critically low (Table 1). Typically, crops utilize only 20–50% of applied nitrogen and merely 10–20% of phosphorus, while the remainder is lost through leaching, volatilization, runoff, or chemical fixation in soils. These losses not only impose economic burdens on farmers but also contribute to serious environmental concerns such as groundwater contamination, eutrophication of surface waters, and greenhouse gas emissions.

Table 1. Nutrient use efficiency for different nutrients

S. NO.	Nutrient	Nutrient use efficiency (%)
1.	Nitrogen	20-50
2.	Phosphorus	10-20
3.	Potassium	70-80
4.	Micronutrients	~2

In this context, nanotechnology offers a transformative pathway for sustaining soil health and improving crop productivity. The idea of nanotechnology was first conceptualized by Richard Feynman. Nanotechnology involves manipulating matter at the atomic and molecular scale (1–100 nm). In agriculture, this has led to the development of smart nutrient delivery systems capable of enhancing nutrient availability while minimizing losses. Integration of nano-fertilizers aligns closely with the principles of 4R Nutrient Stewardship (right source, right rate, right time, and right place), enabling precision agriculture that is productive, resource-efficient, and environmentally sustainable (Figure 1). By reducing nutrient runoff and greenhouse gas emissions, nano-fertilizers represent a clean and climate-responsive agricultural technology.

Figure 1. 4R principles of nutrient management

What Are Nano-Fertilizers?

Nano-fertilizers are nutrient formulations engineered using nanotechnology to improve nutrient delivery, synchronization with crop demand, and bioavailability. They consist of nutrients either encapsulated, coated, or structured within nanomaterials, enabling controlled and sustained release. Nanoparticles, defined as ultrafine units with dimensions between 1 and 100 nm (1 nm = 10^{-9} m), possess an exceptionally high surface area-to-volume ratio, allowing them to adsorb and release nutrients efficiently. Typically, nano-fertilizers range from 30–

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40 nm in size and can hold a large quantity of nutrient ions. Their gradual and continuous release pattern ensures better alignment with crop nutrient requirements, thereby enhancing NUE and minimizing losses. Prominent examples include nano urea, nano DAP, nano zinc, and nano copper, which are increasingly being adopted to reduce fertilizer consumption and environmental impacts. In India, liquid nano-fertilizers developed by the Nano Biotechnology Research Centre in collaboration with Indian Farmers Fertilizers Cooperative Limited (IFFCO) represent a significant step toward balanced and judicious nutrient management, especially urea and DAP.

Classification of Nano-Fertilizers

Based on the methodology of preparing, nano-fertilizers can be broadly classified into three categories:

1. **Nanoscale nutrients** – Where the nutrient itself is reduced to nanoscale dimensions.
2. **Nanoscale additives** – Conventional fertilizers modified with nanomaterials to improve performance.
3. **Nanoscale coatings or encapsulations** – Nutrients are enclosed within nanomaterials (e.g., polymers or zeolites) for controlled and targeted release.

Unlike conventional bulk fertilizers, which dissolve rapidly and are prone to losses, nano-fertilizers are designed to respond to environmental triggers or to deliver nutrients directly into plant tissues.

Recently Developed Nano-Fertilizers

To address low NUE, soil degradation, and environmental pollution, a new generation of nano-fertilizers, specifically Nano urea, Nano DAP, and Nano zinc has recently emerged as a sustainable alternative to conventional fertilizers (Photo 1).

- **Nano urea:** Nano urea is a potential component of 4R nutrient stewardship as it delivers nutrients more precisely and supports sustainable farming. As a clean and green technology, nano urea reduces nutrient losses from fields through leaching and gas emissions. By minimizing these losses, nano urea helps to lower environmental footprints and supports climate-smart agriculture. With minute particle size (20–50 nm), high surface area (nearly 10,000 times greater than 1 mm urea prill) and large number of particles (55,000 nitrogen particles over 1 mm urea prill), nano urea exhibits ~80% nitrogen availability, significantly improving NUE and reducing emissions.
- **Nano DAP:** A liquid fertilizer containing 8% nitrogen and 16% phosphorus. Its nano-sized particles (<100 nm) and bio-polymer functionalization enable rapid absorption through seeds and stomata. This efficient and targeted delivery enhance photosynthetic activity and crop yield while minimizing environmental impact.
- **Nano zinc:** It contains 1% zinc and boosts plant growth by improving nutrient uptake and root proliferation. It enhances flowering and fruit set in crops. Nano zinc protects crops against abiotic stresses and thus, promoting resilience. It increases crop yield by improving overall physiological processes.
- **Nano copper**: It contains 0.80% copper with 5% chelating agents, offering enhanced stability, bioavailability, and protection against abiotic stresses.

Figure 2. Recently developed nano-fertilizers and application in mustard crop

ISSN: 3049-2289

Mechanism of Action: How Nano-Fertilizers Work

Nano-fertilizers exhibit superior NUE due to their unique physicochemical properties, including small particle size and high reactivity. These characteristics enable them to overcome biological barriers more effectively than bulk fertilizers. Foliar application, in particular, offers rapid correction of nutrient deficiencies by bypassing soil-related constraints. Nanoparticles bypass the root system to enter the plant metabolism directly.

Step A: Surface Penetration - Nanoparticles encounter the leaf surface and enter through two main routes:

- **Stomatal pathway**: The primary entry point or route, where nanoparticles pass through open stomata depending on stomatal density and aperture.
- **Cuticular pathway**: Nanoparticles can also diffuse through the waxy cuticle and the epidermis. While the cuticle is a barrier to water loss, the lipophilic or hydrophilic coating of nano-fertilizers can facilitate their penetration through cuticular pores.

Step B: Mesophyll Transport - Once inside the sub-stomatal cavity or epidermal cells, nanoparticles move through the mesophyll tissue (site of photosynthesis) via:

- **Apoplastic movement**: Movement through cell walls and intercellular spaces (red arrows).
- **Symplastic movement:** Movement through the cytoplasm and plasmodesmata of mesophyll cells (green arrows).

Step C: Phloem Loading and Systemic Translocation - Unlike root-based uptake dominated by xylem flow, foliar-absorbed nanoparticles can enter the phloem, enabling bidirectional transport of nutrients to developing leaves, roots, grains, and fruits.

Key Advantages for Sustainable Agriculture

The effectiveness of nano-fertilizers lies in their massive surface area-to-volume ratio and their ability to penetrate plant pores (stomata and cuticles) more easily. The transition from bulk fertilizers to nano-formulations offers several transformative benefits:

- **Higher NUE:** The enhanced penetration and targeted delivery can increase NUE by 20-30% as compared to conventional fertilizers.
- **Cost efficiency:** The higher nutrient absorption and reduced wastage ultimately lead to cost savings for the farmers. Moreover, reduced application rates, lower transportation and storage costs, and fewer applications make them more economically viable. Although the per-unit cost of nano-fertilizers may be higher, the quantity required drastically reduced e.g., a single 500 ml bottle can replace a 45 kg bag of conventional urea.
- **Increased crop yield:** A key advantage of nano-fertilizers is their ability to enhance crop health and significantly boost yields. By delivering nutrients with precision, nano-fertilizers create optimal growth conditions resulting in improved plant vigour and productivity.
- **Controlled and slow release:** Nano-fertilizers are developed as controlled and slow-release formulations, matching nutrient supply with crop demand. This prevents the boom and bust cycle of nutrient availability often seen with conventional urea.
- **Reduced nutrient fixation:** Nano-coatings prevent nutrients (like phosphorus) from chemically reacting with soil ions and becoming insoluble (fixed) in soil, keeping them available for the roots.
- **Environmental protection:** By minimizing leaching and runoff, nano-fertilizers significantly reduce the contamination of water bodies and

ISSN: 3049-2289

reduce emission of greenhouse gases (like nitrous oxide) from agricultural fields.

- **Enhanced stress tolerance:** Specific nano-particles (like silicon or zinc oxide nanoparticles) have been shown to enhance crops' resistance to drought, salinity, and disease.

Current Challenges

Despite their promise, nano-fertilizers face several challenges.

- **Early stage development:** Nanotechnology-based delivery systems are still a nascent field requiring extensive field validation.
- **Limited long-term evidence:** There is currently insufficient evidence that nanocarrier-based fertilizers definitely boost fertilizer use efficiency or significantly lower environmental hazards compared to conventional fertilizers.
- **Biosafety and toxicity concerns:** High concentrations of nanomaterials can be harmful to plant growth, particularly the accumulation of nanoparticles in soils and food chains.

Future Perspectives

Optimization of nano-based nitrogen and phosphorus fertilizers is necessary to improve nutrient-use efficiency under field conditions. Field-scale evaluation of micronutrient nano-fertilizers is required to assess their bioavailability, biofortification potential, and phytotoxic risks. The development of cost-effective, biodegradable nanocarriers with controlled release and soil–root anchoring properties is essential. Establishing safety thresholds and conducting long-term environmental and food-chain risk assessments are critical to prevent nano-toxicity. In addition, standardized regulations for the production and labeling of nano-agricultural inputs are needed to ensure quality, efficacy, and safety

Conclusion

Nano-fertilizers represent a frontier technology poised to drive the Second Green Revolution by addressing the twin challenges of low fertilizer efficiency and environmental degradation. With robust regulatory frameworks, long-term field trials, and farmer awareness, nano-fertilizers can become an integral component of precision and climate-smart agriculture. Ultimately, these technologies demonstrate that small-scale innovations can deliver large-scale solutions for sustainable food production.

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How Urea and Citric Acid Influence Garlic (*Allium sativum* L.) Growth and Yield

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1. Introduction

Garlic cultivation has a long and well-documented history stretching back thousands of years. It remains one of the most widely grown crops today, serving both culinary and medicinal purposes across virtually every culture. Despite this importance, actual garlic yields on farms frequently fall below what the crop is biologically capable of producing. A significant contributing factor is inadequate nutritional management, especially a shortage of nitrogen in the soil. Nitrogen is a foundational element for crop development — without it, plants struggle to build the structural and functional compounds they need to grow vigorously.

Urea — chemically represented as CO(NH2)2 — is the most nitrogen-concentrated solid fertilizer in widespread use, carrying roughly 46% nitrogen by weight. Its affordability, ease of handling, and high nutrient content have made it a go-to choice for garlic growers in many parts of the world. Meanwhile, citric acid, which naturally occurs in many fruits and is secreted by plant roots under nutrient stress, is attracting growing interest as both a soil conditioner and a leaf spray that enhances nutrient uptake and supports plant function.

A clearer understanding of how urea and citric acid work — individually and potentially together — can equip farmers with practical tools to raise healthier garlic crops and achieve more satisfying yields.

2. Garlic as a Nutritionally Demanding Crop

Compared to many other vegetables, garlic has a relatively high appetite for nutrients. It draws heavily on the soil's mineral resources throughout its growing cycle, with nitrogen occupying a particularly important position. This element is central to the production of proteins and enzymes that regulate plant functions, and it is also a core component of chlorophyll, the molecule responsible for capturing light energy and driving photosynthesis. When garlic plants have adequate nitrogen, the results are clearly visible: taller stems, more numerous and well-expanded leaves, and bulbs that fill out properly before harvest.

Phosphorus, too, plays a critical part — especially when it comes to root system development and the actual bulking of the garlic bulb. The difficulty is that phosphorus in many agricultural soils exists in chemically bound forms that roots cannot access directly. This limitation is particularly pronounced in soils that are either highly alkaline or rich in clay minerals. This is precisely where citric acid enters the picture, as its chemical properties allow it to loosen some of those phosphorus bonds, making the nutrient available for uptake.

3. Urea and Its Role in Garlic Development

3.1 The Importance of Nitrogen for Garlic Plants

Nitrogen can be thought of as the primary driver of growth in garlic. Research has consistently demonstrated that adequate nitrogen nutrition results in more robust vegetative development, improved leaf production, and significantly larger bulb size at harvest (Stork *et al.*, 2004, as cited in Sah *et al.,* 2018). Nitrogen-starved garlic plants, on the other hand, display characteristic signs of deficiency: yellowing foliage, stunted growth, and disappointing bulbs that carry little commercial value.

ISSN: 3049-2289

3.2 How Urea Affects Garlic Growth Measurements

A substantial body of research supports the connection between urea application and improved garlic growth. Trials conducted in Egypt demonstrated that raising the nitrogen fertilizer rate from 60 to 120 kg N per feddan brought measurable gains in plant height, leaf count, and both fresh and dry leaf biomass (Sah *et al.,* 2018). In Ethiopia, a study applying urea-sourced nitrogen at rates spanning from zero to 157.5 kg/ha found that nitrogen supply made a substantial difference to nearly every growth parameter observed — including stem height, leaf number, neck thickness, and leaf area index — assessed at several points during the growing season (Negasa *et al*., 2021).

A separate Ethiopian experiment comparing three nitrogen levels — none, 92, and 138 kg N/ha — showed that higher application rates translated into heavier bulbs, wider bulb diameters, greater clove weight, improved harvest index, and higher overall biological yield. Plants in the highest-nitrogen treatment reached average heights of 58.83 cm and carried up to 7.47 leaves per plant under well-managed conditions (Academia.edu, 2020).

3.3 Urea's Effect on Bulb Yield and Post-Harvest Quality

The most commercially important outcome of nitrogen fertilization in garlic is its influence on the bulb itself. Field trials found that applying the full recommended nitrogen rate through inorganic sources — combined with biofertilizer — produced notable improvements across multiple quality indicators. These included an approximately 16.46% increase in the number of cloves per bulb, better clove dimensions, higher average clove weight (recorded at 1.56 g), and elevated concentrations of nitrogen, phosphorus, and potassium within the harvested bulb tissue (Manda *et al.,* 2024). Shelf life and storage behaviour of the bulbs also improved under optimized nitrogen management.

An interesting related finding from the same study involved nano-urea, a newer formulation engineered into extremely fine particles. Applied foliarly at 75 ml/ha, nano-urea produced the highest clove count per bulb, superior clove dimensions, and the greatest nutrient content — suggesting that even modest, precisely delivered quantities of nitrogen can produce meaningful quality gains in garlic (Manda *et al*., 2024).

3.4 Timing Urea Applications for Maximum Benefit

It is not just how much urea is applied, but when it is applied, that determines its effectiveness. Research findings support the practice of splitting the total urea dose across two or more applications. A common recommendation is to apply approximately half the total nitrogen amount at or near planting, with the remaining half delivered around 45 days after transplanting. This staged approach ensures that nitrogen is present in the root zone at the growth stages when the plant needs it most, while reducing the proportion that might be lost to leaching or volatilization (Academia.edu, 2020; Woldemariam *et al.,* 2014).

3.5 Foliar Urea Application as a Complement to Soil Application

Urea is traditionally incorporated into or applied to the soil, but foliar spraying — applying diluted urea solutions directly to the leaf surface — has also been investigated as a supplementary strategy. This approach becomes especially relevant in conditions where root nutrient uptake may be restricted, such as during cool spells or periods of waterlogged soil. Because foliar-applied nutrients are absorbed through the leaf cuticle rather than through the root system, they bypass soil-related barriers and can reach the plant more quickly. Research on garlic supports the value of combining ground-applied nitrogen management with targeted foliar urea treatments, noting improvements in overall yield and

ISSN: 3049-2289

bulb quality compared to soil application alone (Manda *et al.,* 2024).

4. Citric Acid and Garlic Growth

4.1 What Citric Acid Is and How It Functions

Citric acid is a short-chain organic acid that occurs widely in nature. Plants produce and actively release it from their root tips, particularly when they are experiencing difficulty in absorbing phosphorus from surrounding soil. It belongs to the group of low-molecular-weight organic acids — which also includes oxalic and malic acid — and these compounds are known to interact with soil chemistry in ways that can benefit plant nutrition.

When citric acid comes into contact with soil particles, it has the ability to dislodge phosphorus that has become chemically attached to iron and aluminum compounds in acidic soils, or to calcium-containing minerals in alkaline soils. By doing so, it releases previously unavailable phosphorus into the soil water, where plant roots can take it up (Zhu *et al.*, 2022; ScienceDirect, 2021). In essence, citric acid serves as a natural key that unlocks phosphorus stores that would otherwise remain inaccessible.

4.2 Citric Acid's Influence on Phosphorus Availability

Among the various organic acids studied for their ability to increase soil phosphorus availability, citric acid is consistently ranked as one of the most effective. It works partly by competing with phosphorus ions for binding sites on mineral surfaces and partly by chemically dissolving mineral compounds that hold phosphorus in place (ScienceDirect, 2021). Evidence from pot-based experiments on soybean indicated that applying citric acid at 7.5 kg/ha improved plant height, seed development, and the uptake of both phosphorus and nitrogen compared to untreated controls (ResearchGate, 2024).

Given that garlic has a significant phosphorus requirement — particularly during the phases of bulb initiation and bulb enlargement — the phosphorus-mobilizing action of citric acid carries direct practical relevance for garlic production systems, especially those operating on soils with phosphorus fixation problems.

4.3 Foliar Application of Citric Acid on Garlic

Beyond its soil-applied effects, citric acid has also been tested as a foliar treatment for garlic. Research carried out in Egypt on garlic receiving phosphorus and potassium fertilization examined the effects of spraying antioxidant compounds — including citric acid at a concentration of 300 parts per million — on growth characteristics, yield components, and the chemical composition of bulbs (Academia.edu, 2025). Positive results were noted on growth performance and yield traits when citric acid sprays were combined with suitable mineral nutrition.

Supporting evidence from other crops adds further weight to this finding. Foliar treatments with citric acid and related organic acids have been reported to influence plant architecture, stimulate flowering responses, and enhance overall metabolic activity in a range of crop species (ResearchGate, 2014). In experiments involving heavy-metal-stressed conditions, citric acid applications improved biomass accumulation, chlorophyll levels, and antioxidant enzyme function in Brassica napus plants (ResearchGate, 2018).

4.4 Effects on Soil pH and Micronutrient Availability

Alkaline soil conditions are a widespread challenge in many garlic-producing regions. Under high soil pH, essential micronutrients — including iron, manganese, zinc, and copper — tend to precipitate into insoluble forms that roots cannot absorb, and phosphorus availability is also curtailed (Xitrical, 2025). Citric acid can help counteract this problem by mildly acidifying the soil around the root zone, thereby shifting the chemical equilibrium so that more of these nutrients remain in dissolved, plant-accessible forms. In drip irrigation systems, where acidified water can be delivered with precision to the root zone, this effect can be managed in a particularly targeted and efficient way.

4.5 Citric Acid's Internal Role in Plant Metabolism

The significance of citric acid extends beyond its activity in the soil. Within plant cells, citric acid is one of the central molecules of the tricarboxylic acid cycle — commonly known as the Krebs cycle — a fundamental metabolic pathway through which cells extract energy from sugars and organic molecules. This means that citric acid is not merely an external soil conditioner but a molecule with direct functional relevance inside the plant. Providing supplemental citric acid — whether through root absorption from soil application or through foliar uptake — may therefore reinforce these internal metabolic processes, contributing to better energy generation, improved synthesis of organic compounds, and more stable regulation of cellular chemistry.

5. What Happens When Urea and Citric Acid Are Used Together

5.1 The Case for Combined Application

Applying urea and citric acid together creates conditions in which the strengths of each input can potentially reinforce the other. Urea drives nitrogen-dependent processes — particularly the rapid vegetative growth, leaf area development, and chlorophyll production that form the foundation of high yield potential. Citric acid, in parallel, enhances the availability of phosphorus and micronutrients that are essential for root function and bulb development, while also providing antioxidant support to plant cells. Since the two inputs address largely separate nutritional and physiological needs, their combination covers a broader range of limiting factors than either could address alone.

Existing research on garlic supports this logic. Trials that combined recommended nitrogen fertilizer rates with foliar biostimulant applications — which share functional overlap with citric acid's effects — recorded the highest observed values for plant growth, bulb weight, and total yield across consecutive growing seasons (Semanticscholar.org, 2014).

5.2 Chlorophyll Production and Photosynthetic Capacity

Both urea-derived nitrogen and citric acid have documented effects on the photosynthetic performance of plants, though through different pathways. Nitrogen is structurally embedded in the chlorophyll molecule itself, so better nitrogen supply directly translates into more chlorophyll per unit of leaf area and, consequently, a higher capacity for light capture and carbon fixation. Citric acid contributes in a complementary way: by acting as an antioxidant, it helps shield chlorophyll from degradation caused by reactive oxygen species — a form of cellular oxidative damage that becomes more likely under stress conditions. Field data showing that nitrogen management combined with foliar spray treatments elevates leaf chlorophyll readings supports the conclusion that these inputs, used together, can sustain more efficient photosynthesis throughout the growing season (ResearchGate, 2014).

5.3 Bulb Quality and Storability

For garlic producers, bulb quality at harvest — encompassing size, clove number, dry matter concentration, and how well the bulbs hold up during storage — is ultimately what determines income and market success. Evidence from the reviewed studies indicates that well-managed nitrogen fertilization through urea improves all of these characteristics in meaningful ways. Citric acid's role in boosting nutrient absorption efficiency and protecting plant cells from oxidative stress may provide further benefits, particularly in supporting the bulb-filling process and maintaining quality during the post-harvest period. Research from Manda et al. (2024) specifically noted that nitrogen management choices in garlic had measurable downstream effects on weight loss during storage and on the rate at which bulbs began to sprout — both commercially important quality indicators.

6. Practical Guidance for Growers

Drawing on the body of research covered in this review, the following recommendations are offered as general guidance for garlic farmers who wish to incorporate urea and citric acid into their crop nutrition programs:

Urea Application:

- Split the total urea dose across at least two applications — roughly half at or just before planting and the remainder around six weeks after transplanting. This ensures nitrogen is available at peak demand and reduces environmental losses.
- A total nitrogen rate in the range of 92 to 120 kg N per hectare is widely supported by research across diverse growing regions, though the ideal rate for any specific farm should be adjusted based on soil testing and the variety being grown.
- Foliar urea sprays during the leaf expansion phase and the onset of bulb development can usefully supplement soil-applied nitrogen, especially when root activity is constrained by environmental conditions.
- Avoid over-applying nitrogen. Excess urea can push crops toward excessive vegetative growth at the expense of bulb development, and may prolong time to maturity or increase susceptibility to foliar diseases.

Citric Acid Application:

- Citric acid can be delivered either as a soil drench around the root zone or as a foliar spray applied to the leaf surface; research has found both methods to be effective under appropriate conditions.
- For foliar application, a solution concentration of approximately 300 ppm (0.3 grams per litre of water) has been used in research trials with favourable results.
- The benefits of citric acid are likely to be most pronounced on soils that are alkaline in reaction or that have a strong tendency to fix phosphorus — conditions under which soil phosphorus is most likely to be limiting.
- Combining citric acid with phosphorus fertilizer, rather than relying on one or the other alone, generally produces more consistent improvements in phosphorus nutrition and crop response.

7. Conclusion

The research evidence reviewed here makes a compelling case that both urea and citric acid offer genuine, measurable benefits to garlic farmers, each working through its own distinct set of mechanisms. Urea delivers the nitrogen that garlic plants need to grow vigorously, produce an expansive canopy, and ultimately channel energy into large, well-developed bulbs with good keeping quality. Citric acid, through its capacity to improve phosphorus and micronutrient availability in the soil, its support of internal plant metabolic processes, and its protective effects against oxidative cellular damage, provides a different but equally valuable form of nutritional support.

When these two inputs are used together in a thoughtfully designed fertility program — with urea applied at the right rates and appropriate intervals, and citric acid incorporated as either a soil amendment or foliar treatment — there is solid reason to expect meaningful improvements in garlic productivity, bulb quality, and farm profitability. Research specifically examining the joint application of urea and citric acid in garlic production is still relatively limited, and further field trials under a range of soil types and climatic conditions would help to refine recommendations. Nevertheless, the evidence gathered from related studies provides a sound basis for concluding that this combined approach holds real promise.

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Acting locally: Impact globally

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Today is International Biodiversity Day. The United Nations celebrate International Biodiversity Day or World Biodiversity day on May 22, every year. It is celebrated to thank nature and what all it bring to us. This global event which is held on the 22nd of May since year 2000 was first celebrated in 1993. From 1993 to 2000, the day was originally celebrated on December 29 to mark the date the Convention on Biodiversity officially went into effect. In December 2000, the UN General Assembly shifted the observance to May 22. This was done to commemorate the 1992 adoption and to make it easier for countries to plan and host events, avoiding late-December holiday. The day aims to promote and raise global awareness of issues related to the planet's biodiversity.

Let us first understand what Biodiversity is and what is the need to give so much attention to it' The word 'Biodiversity' has been generated from two words 'biological' and 'diversity'. It refers to all the variety of life that can be found on earth like plants, animals, fungi and micro-organisms. Also, it refers to the communities that they form and the habitats in which they live. The article 2 of the Convention on Biological Diversity (CBD) has given a formal definition of Biological diversity. The Biological Diversity there is defined as the variability among living organisms from all sources including inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems. Thus we can say that 'Biodiversity' is the combination of life forms and their interactions with each other and with the rest of the environment that has made Earth is a uniquely habitable place for humans. Its rich biodiversity has been a source of life to millions and millions of different organisims on this planet. Biodiversity provides us a large number of goods and services that sustain our lives. It encompasses a variety of life on earth and the natural patterns it forms. The biodiversity we see today is the fruit of billions of years of evolution, shaped by natural processes and, increasingly by the influence of humans. It forms the web of life of which we are an integral part and upon which we so fully depend.

Unfortunately, when human being today is not looking to fulfill their needs, but has moved towards greed. The large scale destruction of trees, the hunting of animals, the pollution of water bodies, the air we breathe, the degradation of soil and the loss of soil fertility all are the consequences of human being playing with nature. Playing with nature brought havoc on this planet. The most worrisome part is that the human interference with nature has resulted in a loss of biodiversity. In the last hundred years, more than 90 percent of crop varieties have disappeared from farmers' fields. Half of the breeds of many domestic animals have been lost, and all of the world's 17 main fishing grounds are now being fished at or above their sustainable limits. Locally-varied food production systems are under threat, including related indigenous, traditional and local knowledge. With this decline, agro biodiversity is disappearing, and also essential knowledge of traditional medicine and local foods. The loss of diverse diets is directly linked to diseases or health risk factors, such as diabetes, obesity and malnutrition, and has a direct impact on the availability of traditional medicines. Biological resources are the pillars upon which we build civilizations. The loss of biodiversity threatens our

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food supplies, opportunities for recreation and tourism, and sources of wood, medicines, and energy.

The United Nations does celebrate this day with different themes every year. Celebrating such days with a specific theme aims to leverage knowledge and spread awareness of the dependency of our food systems, nutrition, and health on biodiversity and healthy ecosystems. This all has the ultimate aim of conserving our precious biodiversity. This year the theme of the day is 'Acting locally for global impact'. The theme gives a call to all of us to take action to halt and reverse biodiversity loss. Protecting biodiversity includes action close to home with positive ripple effects that can reach far beyond. Our actions at the local level can have very positive impacts at global level. If each one of us maintains a very peaceful and harmonious relationship with nature, the planet would be a far better place to live Safeguarding life on this planet and reversing biodiversity loss is not the job of government alone, it requires action from all segments of the society.

Biodiversity conservation can go a long way in sustainable development. It is not wrong to the say that bio-diversity remains the answer to several sustainable development challenges. From nature-based solutions to climate, health issues, food and water security, and sustainable livelihoods, biodiversity is the foundation upon which we can build back better. From ecosystem-based approaches to climate and/or nature-based solutions to climate, health issues, food and water security and sustainable livelihoods, biodiversity is the foundation upon which we can build back better. That is the main message from the CBD, key international instrument for sustainable development.

For halting biodiversity loss, we have to go for practices like organic and natural farming which conserve our biodiversity. At the same time, we have to avoid single-use plastics like plastic straws, coffee cups, plastic cutlery, take out containers or plastic water bottles and promotion of local and indigenous biodiversity for food and nutrition are some of the issues which we have to look into and adopt in our daily life; if we are serious to conserve our biodiversity and our planet. We also need to support the implementation of the Kunming-Montreal Global Biodiversity Framework also referred to as the Biodiversity Plan. Brundtland commission has also identified three pillars of sustainable development. These are social, economic and environmental and all the pillars are very delicately interrelated. It is not possible to achieve sustainable and inclusive development by excluding any one of the three pillars.

This year's theme of the global campaign highlights how actions taken in communities around the world contribute to the implementation of the Kunming–Montreal Global Biodiversity Framework and to the collective effort to halt and reverse biodiversity loss. It emphasizes upon how from indigenous peoples and local communities, cities and local authorities, to youth, women, businesses and civil society, biodiversity action is strongest when it is driven by a whole-of-society approach. Local initiatives and partnerships play a vital role in turning global commitments into meaningful change on the ground. In the lead-up to COP17 of the Convention on Biological Diversity, the 2026 campaign is also an opportunity for all of us to showcase how local actions around the world are helping/can help in halting biodiversity loss as well as in achieving various targets set up under SDGs 2030.

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Metabolomics: Decoding the Chemical Language of Plants

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Introduction

Agriculture is facing major challenges such as climate change, emerging plant diseases, declining soil fertility and increasing global food demand. To address these issues, modern agricultural research is adopting advanced technologies that help improve crop productivity and sustainability. Among these technologies, metabolomics has emerged as a promising scientific approach in recent years. Metabolomics is the comprehensive study of small chemical compounds known as metabolites that are produced during metabolic activities in living organisms. These metabolites include sugars, amino acids, organic acids, fatty acids, hormones, phenolics, flavonoids and alkaloids. The complete set of metabolites present in an organism is called the metabolome. Since metabolites directly reflect the physiological and biochemical status of plants, metabolomics provides real-time information about plant health and stress responses. Unlike genomics, which studies genes, metabolomics helps researchers understand what is actually happening inside plants under different environmental conditions. Plants produce various metabolites in response to biotic stresses such as pathogens and abiotic stresses such as drought, salinity and heat. By analysing these metabolites, scientists can identify disease resistant and stress tolerant crop varieties and develop sustainable crop management strategies. Metabolomics has wide applications in agriculture, including crop improvement, plant disease management, food quality analysis and environmental studies. Advanced analytical techniques such as Gas Chromatography Mass Spectrometry (GCMS), Liquid Chromatography Mass Spectrometry (LCMS) and Nuclear Magnetic Resonance (NMR) are commonly used for metabolomic studies. Thus, metabolomics is becoming an important tool for achieving sustainable agriculture, climate resilience and global food security.

What is Metabolomics?

Metabolomics is the scientific study of small molecular compounds called metabolites that are produced during various metabolic processes inside living organisms. These metabolites are essential for maintaining normal growth, development and physiological activities. They include a wide range of compounds such as sugars, amino acids, organic acids, fatty acids, phenolics, flavonoids, alkaloids, vitamins and plant hormones. The complete set of metabolites present in a cell, tissue, or organism at a particular time is known as the metabolome. The metabolome is highly dynamic and changes continuously in response to environmental conditions, developmental stages, nutrient availability, pathogen infection and other stress factors. Metabolomics aims to identify, quantify and analyse these metabolites to understand the biochemical and physiological status of an organism. Unlike genomics, which studies the genetic makeup of an organism or proteomics, which focuses on proteins, metabolomics provides direct information about the actual functional state of cells and tissues. Since metabolites are the final products of cellular activities, they closely reflect the ongoing biological processes within the organism. In plants, metabolomics helps researchers understand how crops respond to both biotic stresses such as pathogens and pests, and abiotic stresses such as drought, salinity, heat and nutrient deficiency. Stress conditions often alter metabolic pathways, leading to the production of defense related compounds like phenolics, antioxidants, flavonoids and phytoalexins. Because metabolites respond rapidly to internal and external changes, metabolomics provides a real time snapshot of plant health and metabolism. Therefore, it has become an important tool in modern agriculture for crop improvement, disease diagnosis, stress tolerance studies, food quality analysis and sustainable crop management practices.

Importance of Metabolomics in Agriculture

Metabolomics has emerged as one of the most important and advanced tools in modern agricultural research. It helps scientists study the biochemical processes occurring inside plants and understand how plants respond to different environmental and biological stresses. Since metabolites are the end products of cellular activities, changes in their levels provide direct information about the physiological condition of plants. Plants are continuously exposed to various biotic and abiotic stresses such as disease infection, drought, salinity, nutrient deficiency, heat stress, cold stress and pest attack. Under such stressful conditions, plants undergo several metabolic and biochemical changes and produce specific stress related compounds to survive adverse environments. Metabolomics helps identify and analyse these compounds, thereby enabling researchers to understand plant defense mechanisms and stress adaptation processes. In plant pathology, metabolomics plays a crucial role in studying host pathogen interactions. When pathogens infect plants, several defense metabolites such as phenolics, flavonoids, phytoalexins, antioxidants and organic acids are produced. By studying these metabolites, scientists can identify resistant crop varieties and develop effective disease management strategies. Metabolomics also helps in early disease diagnosis through the identification of disease specific biomarkers. Metabolomics is equally important in abiotic stress management. Environmental stresses like drought, salinity and high temperature significantly affect plant growth and yield. Metabolomic studies help identify stress responsive metabolites and pathways associated with tolerance mechanisms. This information is useful for developing climate resilient and stress tolerant crop varieties. In addition, metabolomics contributes to crop improvement, food quality analysis, nutritional enhancement and precision agriculture. It also supports sustainable farming by promoting the use of biological control agents, microbial consortia and organic amendments, thereby reducing excessive dependence on chemical fertilizers and pesticides. Thus, metabolomics is becoming an essential tool for improving crop productivity, enhancing stress tolerance, ensuring food security and achieving sustainable agricultural development.

Metabolomics in Plant Disease Management

Plant diseases caused by fungi, bacteria, viruses and nematodes are major constraints to agricultural productivity worldwide. These diseases reduce crop yield, affect produce quality and cause significant economic losses to farmers. During pathogen attack, plants undergo several physiological, biochemical and metabolic changes as part of their natural defense response. Plants produce various defense-related metabolites such as phenolics, flavonoids, phytoalexins, alkaloids, antioxidants, terpenoids and organic acids that help suppress pathogen growth and protect plant tissues from damage. Metabolomics has emerged as a powerful tool for studying these complex biochemical interactions between plants and pathogens. By analysing the metabolites produced during infection, researchers can better understand host pathogen interactions and plant defense mechanisms. Metabolomic studies help identify metabolic pathways associated with disease resistance and stress responses in plants. One of the important applications of metabolomics in plant pathology is the identification of disease biomarkers. Specific metabolites produced during infection can serve as early indicators of disease development even before visible symptoms appear. This supports early disease diagnosis and timely management practices. Metabolomics also assists researchers in identifying resistant crop varieties by comparing the metabolic profiles of resistant and susceptible plants. In addition, it is widely used to evaluate the effectiveness of biocontrol agents, microbial consortia, plant extracts and organic amendments in disease suppression. Thus, metabolomics plays a significant role in sustainable plant disease management by supporting early diagnosis, resistance breeding, eco-friendly disease control and environmentally safe agricultural practices.

Future Prospects

The future of metabolomics in agriculture is highly promising with the integration of genomics, proteomics, artificial intelligence and machine learning technologies. Metabolomics can contribute to climate smart agriculture, precision breeding, early disease diagnosis, reduced pesticide dependence and sustainable crop production. In the coming years, it is expected to play a major role in improving food security and environmentally safe agricultural practices.

Conclusion

Metabolomics is becoming an important tool in modern plant disease management. It helps researchers understand plant defense responses, identify disease biomarkers, evaluate resistant varieties and develop eco-friendly disease management strategies. With advances in analytical technologies and bioinformatics, metabolomics is expected to play a major role in sustainable crop protection and future agricultural development.

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Garlic: Nutrition Facts and Health Benefits

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Introduction

Walk into any kitchen around the world and you will almost certainly find garlic sitting somewhere nearby. It is one of those rare ingredients that belongs equally to the cook and the healer. Long before modern medicine arrived, ancient Egyptians handed cloves of garlic to labourer building the pyramids, believing it kept them strong and disease-free. Greek physicians prescribed it for a range of ailments. Soldiers across many cultures carried it into battle as a natural wound remedy.

Fast-forward to today, and science has largely caught up with what those early civilizations seemed to understand intuitively. Garlic (*Allium sativum*) is now one of the most extensively studied plants in nutritional research, and the findings are hard to ignore. Small in size, big in impact — that about sums it up.

What Is Actually Inside Garlic?

We rarely eat garlic by the handful, yet even the small amounts we use regularly can add up to meaningful nutritional input. Here is what a 100-gram serving of raw garlic contains:

Nutrient	Per 100 g (Raw)
Calories	149 kcal
Carbohydrates	33 g
Protein	6.4 g
Dietary Fiber	2.1 g
Fat	0.5 g
Vitamin C	31.2 mg (35% DV)
Vitamin B6	1.24 mg (62% DV)
Manganese	1.67 mg (84% DV)
Selenium	14.2 mcg
Calcium	181 mg
Phosphorus	153 mg
Iron	1.7 mg
Potassium	401 mg

Of course, nobody eats 100 grams of garlic in one sitting — a typical clove weighs around 3 to 5 grams. But the point is that garlic packs a surprising amount of nutrients into a very small package.

The Compounds That Do the Heavy Lifting

Beyond vitamins and minerals, garlic owes most of its therapeutic reputation to a group of sulfur-containing compounds that form when its cells are broken open:

- Allicin — This is the star of the show. It forms only when raw garlic is crushed, chopped, or chewed — a chemical reaction triggered by the enzyme alliinase. Allicin is responsible for garlic's sharp smell and most of its medicinal properties.
- Diallyl disulfide and diallyl trisulfide — These form as allicin breaks down. Studies link them to benefits for heart health and cancer prevention.
- S-allylcysteine (SAC) — A stable, water-soluble compound found in aged garlic extract. It

survives digestion and delivers steady antioxidant activity.

- Ajoene — Helps prevent blood clots and has shown anti-tumor activity in laboratory settings.
- Quercetin and flavonoids — Plant-based antioxidants that help reduce inflammation throughout the body.
- Fructooligosaccharides (FOS) — Prebiotic fibers that feed the good bacteria living in your gut.

Health Benefits Backed by Research

1. Keeping Your Heart Healthy

This is probably where garlic gets most of its scientific attention. The evidence supporting garlic's role in cardiovascular health is quite solid:

- Blood pressure: Regular garlic consumption has been shown to lower systolic blood pressure by 7 to 9 mmHg and diastolic pressure by 4 to 6 mmHg in people with hypertension. For context, that is comparable to what some prescription medications achieve.
- Cholesterol: Garlic can reduce total cholesterol and LDL (the so-called bad cholesterol) by roughly 10 to 15 percent in people with elevated levels.
- Artery health: The antioxidants in allicin and SAC help stop LDL cholesterol from oxidising — a key step in the build-up of plaque that narrows arteries over time.
- Blood clotting: Certain sulfur compounds in garlic reduce the stickiness of platelets, lowering the risk of dangerous clots that can lead to heart attacks or strokes.

2. Fighting Off Bacteria, Fungi, and Viruses

Long before antibiotics existed, garlic was a go-to natural remedy for infections. There is good reason for that. Allicin essentially disarms microorganisms by interfering with the enzymes they need to survive and reproduce.

- Bacterial infections: Garlic is active against a wide range of bacteria, including Staphylococcus aureus, E. coli, Salmonella, and Helicobacter pylori — the bacterium behind most stomach ulcers. What makes this especially interesting is that garlic retains some effectiveness against antibiotic-resistant strains like MRSA.
- Fungal infections: Studies show garlic can inhibit Candida albicans, the fungus responsible for thrush and other candida-related conditions, performing comparably to certain antifungal medications in lab conditions.
- Viral infections: Early research suggests garlic compounds may interfere with influenza viruses and the common cold virus, though human clinical trials in this area are still limited.

3. Giving Your Immune System a Boost

Garlic does not just fight pathogens directly — it also helps the body fight them better. It stimulates natural killer cells and macrophages, which are the immune system's frontline soldiers. It also encourages the growth of lymphocytes and increases the production of cytokines, which coordinate the body's immune response.

One well-known 12-week study found that people taking a daily garlic supplement got 63% fewer colds than those taking a placebo. And when they did catch a cold, their symptoms cleared up noticeably faster. That is a fairly compelling result for something you can buy at any grocery store.

4. Potential Role in Cancer Prevention

Populations that traditionally eat a lot of garlic tend to have lower rates of stomach, colon, and certain other cancers. Researchers have worked to understand why, and the lab findings give some useful clues:

- Garlic's sulfur compounds appear to block carcinogenic substances from activating inside the body and help accelerate their removal.

- Allicin and diallyl trisulfide can trigger apoptosis — a kind of self-destruct mechanism — in cancer cells, while leaving healthy cells unharmed.
- Garlic may also interfere with angiogenesis, the process by which tumours build new blood vessels to feed their growth.
- The World Health Organization has acknowledged garlic's potential contribution to cancer prevention in its dietary recommendations.

A word of caution though: garlic is not a cancer treatment, and it should not be treated as one. What the evidence suggests is that making it a consistent part of a balanced diet may reduce your risk over time — which is a meaningful but different claim.

5. Supporting Blood Sugar Control

For people managing type 2 diabetes or trying to prevent it, garlic may offer some worthwhile support. Research points to several ways it influences blood sugar:

- It improves insulin sensitivity, helping the body's cells respond better to insulin and use glucose more efficiently.
- It can lower fasting blood glucose levels in people with diabetes.
- It has been linked to reductions in HbA1c — the marker doctors use to track average blood sugar over a three-month period.
- It slows down the enzyme alpha-glucosidase, which breaks down carbohydrates during digestion. A slower breakdown means a gentler rise in blood sugar after meals.

6. Reducing Inflammation and Oxidative Stress

Chronic low-grade inflammation sits at the root of many of today's most widespread health problems — from joint pain and metabolic syndrome to cardiovascular disease and cognitive decline. Garlic compounds suppress several key inflammatory chemicals in the body, including COX-1, COX-2, TNF-alpha, and IL-6, in a way that echoes how anti-inflammatory drugs work, though considerably milder.

On the antioxidant front, garlic helps neutralise free radicals and also ramps up the body's own antioxidant defence enzymes, including superoxide dismutase and glutathione peroxidase. Essentially, it both does the job itself and trains your body to do it better.

7. Protecting the Liver

Animal studies and cell-based research suggest garlic has a protective effect on liver tissue. It appears to reduce liver damage caused by alcohol, heavy metals, and certain medications by activating detox enzymes and cutting down on fat accumulation within liver cells. Aged garlic extract, in particular, has shown promise in research related to non-alcoholic fatty liver disease (NAFLD), though more human trials are needed to confirm the extent of this benefit.

8. Bone Health

This is an emerging area of research, but there are early signs that garlic may support bone density — particularly in women. Studies in female rats found that garlic oil reduced the bone loss triggered by estrogen deficiency. Diallyl disulfide has also been shown to suppress osteoclast activity (osteoclasts are the cells responsible for breaking down bone tissue), suggesting garlic could have a role to play in osteoporosis prevention. Human studies are needed to build on these findings.

How to Get the Most Out of Garlic

- Crush it and wait a few minutes. Allicin only forms after the cell walls are broken. Crushing or finely chopping garlic and letting it sit for 10 to 15 minutes gives the enzyme reaction time to complete before heat can interfere.
- Raw is best when possible. Temperatures above 60°C (140°F) start to degrade allicin fairly quickly. Adding raw garlic to salad dressings or stirring it into dishes just before serving helps preserve the active compounds.

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- Aged garlic extract is a solid alternative. Aging garlic converts allicin into more stable compounds like SAC, which survive cooking and digestion and continue working in the body over time.
- Consistency matters more than quantity. Most of the clinical benefits seen in research come from regular, long-term consumption rather than occasional large doses. A clove or two a day, most days, is a reasonable target.

A Few Things to Keep in Mind

Garlic eaten as food is safe for the vast majority of people. However, there are a few situations where extra caution is warranted:

- Blood thinners: Garlic's anti-platelet effect can amplify the action of anticoagulants like warfarin, aspirin, and clopidogrel, increasing the risk of bleeding. Talk to your doctor if you are on these medications and want to take garlic supplements.
- HIV medications: High-dose garlic supplements may lower blood levels of certain antiretroviral drugs, such as saquinavir, potentially reducing their effectiveness.
- Sensitive stomach: Some people find that eating raw garlic in large amounts causes heartburn, nausea, or digestive discomfort. Starting with smaller amounts usually helps.
- Before surgery: Most healthcare providers recommend stopping garlic supplements at least two weeks before any planned surgery due to the bleeding risk.
- Pregnancy: Culinary use is generally considered safe, but taking garlic in medicinal doses during pregnancy should be discussed with a doctor first.

Conclusion:

Garlic is one of those genuinely impressive foods that has stood the test of time — not just in the kitchen, but in the medicine cabinet too. Its broad range of benefits, from heart health and immune support to anti-inflammatory and antimicrobial action, is backed by a substantial body of research. It is not a cure-all, and it should not be used as a substitute for medical treatment. But as a regular part of a healthy diet, it is hard to find a cheaper or more versatile ally.

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Millets: Reclaiming an Ancient Grain for a Modern World

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1. Introduction: Why Millets Matter Now

Consider a grandmother in rural Karnataka shaping ragi mudde — compact, dark spheres of finger millet dough — to nourish her grandchildren. Or imagine a farming family in the Sahel harvesting pearl millet in the brief, precious interval between the dry season and the arrival of the rains. Such scenes, replicated across generations in scores of cultures, speak to a food that supported human populations well before the cultivation of rice paddies or wheat fields became widespread.

Millets are not a single crop but rather an umbrella term for a cluster of small-grained cereal species — among the most significant being pearl millet, finger millet, foxtail millet, sorghum, proso millet, barnyard millet, kodo millet, and little millet. Their defining trait is adaptability: they thrive in poor soils, persist under minimal rainfall, and endure intense heat. For centuries, this toughness positioned them as the dietary cornerstone of smallholder agriculture across arid and semi-arid regions of Asia and Africa.

The mid-20th-century Green Revolution altered this trajectory dramatically. As global agricultural policy concentrated resources on high-yield varieties of rice, wheat, and maize, millets lost both field presence and cultural cachet. The dismissive label of "poor man's food" — a phrase that reflects economic bias far more accurately than nutritional reality — took hold.

That narrative is now being overturned. When the United Nations designated 2023 as the International Year of Millets, it formalized what researchers and food advocates had been arguing for years: these grains are not relics of an earlier era but resources for the challenges ahead. At the intersection of climate adaptation and nutritional rehabilitation, millets represent a genuinely forward-looking food solution.

2. Deep Roots: A History Written in Grain

The relationship between millets and human civilization is extraordinarily long. Archaeobotanical records place the cultivation of finger millet in East Africa at approximately 5,000 BCE. Foxtail millet was being domesticated in China between 6,000 and 7,000 BCE, making it one of the earliest crops in the agricultural record. Pearl millet has provided nourishment across the Indian subcontinent and the Sahel for over three millennia.

Every society that grew millets forged a distinct culinary identity around them. In South India, ragi mudde carries associations with physical vitality and familial care. In West Africa, a substantial pearl millet porridge — defines both daily meals and communal celebrations. Boza, a fermented millet beverage from Eastern Europe, has been consumed through cold winters for hundreds of years. These traditions are more than dietary habits; they represent encoded ecological knowledge and cultural continuity.

The Green Revolution, for all its achievements in caloric output, disrupted this knowledge. By prioritizing grain volume over nutritional diversity, it helped create what researchers now describe as "hidden hunger" — a condition in which individuals consume sufficient calories while remaining chronically deficient in iron, zinc, calcium, and essential vitamins. The populations most damaged by this shift were frequently those who had historically depended on millets for precisely those nutrients —

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an irony that has not escaped contemporary food scientists.

3. Nutritional Composition: What Millets Offer

3.1 Carbohydrates and Blood Sugar Response

Millets derive 60–75% of their dry weight from carbohydrates, placing them firmly in the cereal category. However, the metabolic character of those carbohydrates differs meaningfully from what refined alternatives provide. Millet starch digests at a slower rate than the starch in processed rice or white wheat flour, producing a more gradual glucose rise in the bloodstream. Coupled with dietary fiber content that varies from roughly 1.2% to 8.5% depending on species and processing method, millets exert a noticeably gentler effect on blood sugar regulation than the refined staples that currently define global eating patterns.

For the hundreds of millions of individuals living with or at heightened risk of type 2 diabetes — disproportionately concentrated in South Asia and sub-Saharan Africa, where millets were once dietary staples — this is a property with real clinical significance.

3.2 Protein: Modest Volume, Notable Composition

The protein content of millets ranges from approximately 7% to 12% by weight — broadly comparable to rice and somewhat below wheat. What sets particular varieties apart is their amino acid composition. Finger millet stands out for its methionine content, an essential amino acid that is frequently underrepresented in plant-dominant diets. Pearl millet registers the highest protein concentration among the commonly cultivated varieties. While millets cannot match the protein density of animal-based foods, they contribute meaningfully to overall protein quality within a diverse diet that includes legumes.

3.3 Fats: Low in Quantity, Favorable in Profile

Fat constitutes a relatively small fraction of millet composition — between 1.5% and 5%, with pearl millet toward the upper end. The fat present is predominantly unsaturated, with linoleic acid (an omega-6 fatty acid) as the primary component. For communities facing an increasing burden of cardiovascular disease, this lipid profile offers a nutritional advantage worth acknowledging.

3.4 Micronutrients: The Strongest Case for Millets

It is the micronutrient profile of millets that most decisively distinguishes them from other staple cereals. The table below presents comparative data across key minerals and vitamins:

Nutrient	Finger Millet	Pearl Millet	Foxtail Millet	Sorghum
Calcium (mg/100g)	344	42	31	25
Iron (mg/100g)	3.9	8.0	2.8	4.4
Zinc (mg/100g)	2.3	3.1	2.4	1.6
Magnesium (mg/100g)	137	137	81	165
Phosphorus (mg/100g)	283	296	290	287
Thiamine (mg/100g)	0.42	0.38	0.59	0.24

Finger millet's calcium content — 344 mg per 100 grams — is approximately ten times the level found in equivalent quantities of rice or wheat. For growing children, pregnant women, and elderly individuals in communities where dairy consumption is limited, this represents an accessible and culturally familiar pathway to adequate calcium intake.

Pearl millet's iron content — reaching up to 8 mg per 100 grams — is comparable to many meat-based iron sources. In regions where iron deficiency anemia affects the majority of women and children, this is not merely a nutritional data point. It speaks directly to whether a child can develop and perform at their full cognitive and physical potential.

3.5 Bioactive Compounds: Beyond the Nutritional Basics

Millets contain a range of phytochemicals that extend their health relevance well beyond conventional nutritional measures. Polyphenols — including ferulic acid, tannins, and flavonoids — function as antioxidants and anti-inflammatory agents within the body. Finger millet is especially concentrated in ferulic acid. Sorghum contains a distinctive class of antioxidant pigments known as 3-deoxyanthocyanidins, found in no other grain, which have demonstrated meaningful anticancer activity in laboratory settings.

Additionally, millets supply modest quantities of tryptophan — the biochemical precursor to serotonin — at concentrations exceeding those found in maize. The potential neurological and mood-related implications of this are only beginning to be investigated, but the early findings are intriguing.

4. Health Evidence: What Research Demonstrates

4.1 Glycemic Control and Diabetes Management

The interaction between millet consumption and blood glucose regulation is among the best-documented areas of millet research, and the context makes this unsurprising. South Asia — historically the heartland of millet cultivation — now carries the world's largest burden of type 2 diabetes, a transition that correlates chronologically with the displacement of millets by refined rice and wheat from daily diets.

Several biological mechanisms underlie the glycemic advantage millets confer: slower enzymatic breakdown of millet starch, fiber-mediated slowing of intestinal glucose absorption, and polyphenols that directly inhibit carbohydrate-digesting enzymes. Glycemic index values for millet varieties generally fall between 52 and 71, versus approximately 72 for polished white rice. A 2021 meta-analysis in Frontiers in Nutrition demonstrated that substituting refined cereals with millet-based foods produced statistically significant reductions in fasting blood glucose, HbA1c (a long-term marker of blood sugar control), and postprandial glucose elevations in individuals with type 2 diabetes.

4.2 Cardiovascular Protection

Diet ranks among the most modifiable risk factors for cardiovascular disease — the leading cause of death globally. Millets contribute to heart health through multiple pathways simultaneously. Soluble fiber and naturally occurring plant sterols (phytosterols) impede cholesterol absorption in the gut; studies have linked regular foxtail and pearl millet consumption to reductions in LDL cholesterol. Bioactive peptides released during millet protein digestion appear to inhibit ACE — the enzyme centrally involved in blood pressure elevation. Meanwhile, the substantial magnesium content of millets supports healthy vascular tone through yet another independent mechanism.

4.3 Skeletal Health and Calcium Availability

Inadequate calcium intake affects large segments of the global population, particularly women and children in lower-income settings where dairy products are either costly or culturally limited. Finger millet offers a practical, affordable, and culturally grounded alternative calcium source. Research conducted across South Asia has associated habitual ragi consumption with improved bone mineral density in children and lower rates of stress fractures. Critically, the bioavailability of finger millet's calcium is substantially enhanced by fermentation and germination — traditional processing techniques that communities have employed for generations, long before the underlying biochemistry was understood.

4.4 Iron Deficiency and Anemia Prevention

Iron deficiency anemia is the most prevalent nutritional disorder worldwide, affecting an estimated 1.2 billion individuals. Its consequences are serious and far-reaching: blunted cognitive development in children, elevated maternal mortality risk, and diminished economic productivity across entire populations. Pearl millet's iron concentration of up to 8 mg per 100 grams has made it a cornerstone of biofortification strategies in India and West Africa. Field-based interventions in both regions have recorded meaningful increases in hemoglobin levels among school-age children and reproductive-age women following sustained pearl millet consumption.

4.5 A Natural Gluten-Free Option

All varieties of true millet are inherently free of gluten. For the approximately 1% of the global population diagnosed with celiac disease — and the broader population reporting non-celiac gluten sensitivity — this characteristic matters considerably. Beyond that specific community, millets provide a far more nutritionally complete gluten-free alternative than the ultra-processed starch products that dominate commercial gluten-free shelves. A diet that builds its gluten-free foundation on whole millets is nutritionally superior by virtually every metric.

4.6 Gut Microbiome and Digestive Health

The insoluble fiber and resistant starch in millets serve as substrates for beneficial gut bacteria. Traditionally fermented millet products — ogi, kunu, boza, and others — add another dimension by introducing live microbial cultures that enhance both intestinal health and nutrient bioavailability. Emerging microbiome research is beginning to associate millet consumption with greater gut bacterial diversity and reduced inflammatory markers in the intestinal environment. This is an area of inquiry that appears likely to expand significantly in the coming years.

5. Anti-Nutrients: Context and Practical Solutions

An honest discussion of millets must address a genuine complexity: raw millets contain phytates, tannins, oxalates, and enzyme inhibitors that can, in their untreated form, impair the absorption of minerals and proteins. This is not a characteristic unique to millets — legumes, nuts, and many vegetables exhibit similar properties. More importantly, the food preparation practices associated with traditional millet cuisines reliably neutralize these compounds.

Fermentation reduces phytate concentrations by up to 60% while simultaneously improving iron and zinc bioavailability. Germination activates endogenous enzymes that break down anti-nutritional factors while elevating levels of vitamin C and B vitamins. Soaking, roasting, and dehulling each contribute additional reductions. Traditional communities arrived at these techniques through accumulated experience; contemporary food science has since confirmed the biochemical mechanisms behind their effectiveness.

The practical guidance is straightforward: follow traditional preparation — soak, ferment, or sprout millets before cooking — and any concerns about anti-nutritional interference effectively disappear.

6. Climate Resilience: Crops Built for Adversity

6.1 Performing Where Conventional Crops Cannot

Any serious discussion of millets today must engage with climate change. The staple crops that currently underpin global food security — wheat, rice, and maize — face mounting threats from temperature increases, altered precipitation patterns, and

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intensifying extreme weather events. Millets, shaped by evolutionary pressure across some of the most agriculturally demanding environments on Earth, operate under a fundamentally different set of constraints.

They can complete their growth cycle on annual rainfall below 300 millimeters. Their cropping period spans just 60 to 90 days — compact enough to be timed around climate extremes. They impose minimal demands for fertilizer and chemical inputs. They colonize degraded, nutrient-depleted soils that are unsuitable for other crops. In a world of accelerating climate disruption, these are not minor advantages. For the communities most exposed to climate-driven agricultural failure, they represent potential survival.

6.2 Water Efficiency: A Dramatic Contrast

Producing a single kilogram of rice typically requires between 3,000 and 5,000 liters of water. The same kilogram of pearl millet can be produced with as little as 300 to 500 liters — a tenfold reduction in one of the world's most contested natural resources. As groundwater levels fall across South and Central Asia and surface water flows become less predictable, the water efficiency of millets ceases to be merely an agricultural footnote. It becomes a matter of long-term resource security.

6.3 Environmental Footprint

Because millets require fewer chemical inputs and far less water than comparable crops, their greenhouse gas emissions per kilogram of grain are substantially lower than those of rice, wheat, or maize. Life cycle assessments consistently position millets at the upper end of cereal sustainability rankings. As consumers, food companies, and governments increasingly factor emissions into procurement and dietary decisions, this low-footprint profile becomes a meaningful asset.

6.4 Addressing Hidden Hunger at Its Source

Over two billion people globally subsist in a state of hidden hunger — ingesting enough total calories but chronically short of iron, zinc, calcium, or B vitamins. The most durable response to hidden hunger is not supplementation or industrial fortification but dietary diversification: growing and consuming a wider range of foods. Millets — dense in multiple micronutrients simultaneously and producible at very low cost — represent an elegant, food-first answer to a challenge that pharmacological approaches have repeatedly failed to solve at scale.

7. From Traditional Kitchens to Global Markets

The commercial food sector is beginning to absorb the scientific evidence. Millet flours, particularly those derived from sorghum and finger millet, are entering the formulation of breads, biscuits, and snack products — simultaneously improving nutritional value and serving the growing gluten-free segment. Puffed and flaked millet products are appearing in mainstream retail as breakfast and snack options. Traditional fermented beverages such as boza and kunu are gaining commercial momentum on the back of consumer interest in probiotics.

In child and maternal nutrition programs, millet-based complementary foods are being formulated and scaled as micronutrient-dense, energy-adequate options for the most nutritionally critical early-life period. Millet-enriched pasta and grain blends are attracting food innovation investment. Pearl millet remains at the center of biofortification programs targeting iron and zinc deficiency across low-income country contexts.

Genuine challenges remain on the demand side. For consumers outside regions with millet culinary traditions, the flavor profile can be unfamiliar — somewhat earthy, occasionally astringent depending on preparation method. Culinary education and flavor optimization are legitimate prerequisites for broader adoption. Nonetheless, global food culture is more receptive than at any prior moment to novel grains, and millets have the foundational advantage of tasting genuinely good when prepared with care.

8. Policy Landscape: Progress and Remaining Work

The policy environment is evolving, if not yet at the pace the evidence warrants. The UN's International Year of Millets in 2023 generated global visibility and catalyzed research investment. India's Shree Anna (Millets) initiative elevated millets to priority status within national agricultural policy, incorporating them into public distribution systems and school feeding programs that collectively reach hundreds of millions of people. ICRISAT continues to develop drought-tolerant and biofortified millet varieties. Africa's Great Green Wall Initiative is weaving millet cultivation into a broader Sahel land-restoration strategy.

Realizing the full potential of these initiatives requires sustained, systemic follow-through: subsidy structures that correct the competitive imbalance between millets and heavily supported commodity crops; formal inclusion of millets in national dietary guidelines; investment in post-harvest storage and processing infrastructure; and supply chain development that actually connects smallholder producers to remunerative markets. The scientific foundation is solid. Translating it into durable policy is the work that remains.

9. Honest Limitations

A credible assessment of millets must acknowledge their real-world constraints alongside their strengths.

Post-harvest losses remain substantial in smallholder systems — inadequate storage infrastructure means that a significant portion of harvested grain never reaches consumers. Affordable milling and processing equipment is still inaccessible to many producers, constraining product diversity. The persistent association between millets and poverty will require consistent advocacy and cultural reframing to overcome. And while the nutritional science is compelling, the field would benefit from more rigorous, large-scale clinical trials — particularly on cardiovascular and metabolic outcomes — to move beyond epidemiological association toward definitive causal evidence.

These are genuine barriers. They are also, without exception, the kind of barriers that targeted investment and genuine political commitment have the capacity to address.

10. Conclusion: Ancient Knowledge, Contemporary Necessity

Millets converge on answers to several of the defining challenges of our era. They address food insecurity in a world where climate volatility increasingly disrupts staple crop production. They counter malnutrition in populations that consume adequate calories but remain depleted in essential micronutrients. They provide metabolic protection in communities confronting rising rates of diabetes and cardiovascular disease. And they achieve all of this while consuming a fraction of the water, land, and carbon resources required by the dominant crops of the current food system.

There is something worth pausing over in the recognition that grains which nourished human civilization across millennia may be among the most strategically important foods available to us now. The grandmother pressing ragi mudde in Karnataka was not practicing a primitive or outmoded tradition. She was drawing on accumulated nutritional wisdom that modern science has spent decades working to rediscover and confirm.

The renewed interest in millets is not an exercise in nostalgia. It is the convergence of nutritional evidence, ecological necessity, and public health urgency — each pointing independently toward the same grain.

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Algae Tree: A Green Innovation for Cleaner Cities and Sustainable Future

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Urbanization and industrialization have significantly increased air pollution and carbon dioxide emissions worldwide. The Air Quality Index (AQI) is often poor in Indian cities due to emissions from vehicles, industrial smoke and dust. Nowadays, tree plantation is one of the most efficient ways to restore the environment, but the increasing pollution need innovative supplementary technologies, as traditional plantations are not possible in urban areas, and trees grow too slowly. The idea of the "Algae Tree" or "Liquid Tree" has come into existence as a groundbreaking bioengineering approach in urban air purification and carbon capture.

As an algae tree, it is not a natural tree but an algae-based photobioreactor system that is able to capture carbon dioxide (CO_2) and produce oxygen (O_2) via photosynthesis. The technology combines biological, environmental engineering, renewable energy, and smart monitoring systems to produce a cleaner urban environment. The new installations in Serbia and India have recently gained global attention for their innovative approaches to "climate smart cities".

The Science behind Algae Trees – Knowing the Science behind the Algae Trees

Like green plants, microalgae use sunlight, water and carbon dioxide to synthesize biomass and oxygen through photosynthesis. Some algal species have very high CO_2 absorption capacity and high growth rate which is suitable for environmental use.

Algae trees can be simply expressed as the basic photosynthesis process as:

$$6CO_2 + 6H_2O + \text{Light Energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

In algae tree systems, microalgae are cultivated in transparent chambers known as photobioreactors (PBRs). These reactors provide controlled conditions for algal growth including light, nutrients, airflow, temperature, and carbon dioxide supply. Air from the surrounding environment is circulated through the system where microalgae absorb pollutants and convert CO_2 into oxygen-rich biomass.

Components of an Algae Tree System

A modern algae tree generally consists of the following major components:

1. Photobioreactor Chamber: This transparent chamber contains water and selected microalgae strains. Materials such as glass or acrylic panels are used to allow sunlight to penetrate for photosynthesis.

2. Air Circulation System: Polluted ambient air is drawn into the reactor using pumps or blowers. Air bubbles through the algal culture, enable carbon dioxide absorption.

3. Solar Energy Unit: Solar panels provide the power for many algae trees, lessening their reliance on traditional electricity, and making them eco-friendly.

4. Monitoring and Control Sensors: Advanced systems are equipped with IoT-based environmental sensors and AI-powered controllers to monitor: Temperature, pH, Light intensity, Humidity, CO_2 concentration, Air quality parameters

5. Biomass Harvesting Unit: Algal biomass generated in the process of photosynthesis can be harvested and used for Biofertilizers, Biofuels, Animal feeds, Nutraceutical products, Bioplastics.

ISSN: 3049-2289

So algae trees can not only remove CO2 from the air, but also serve as biomass production systems for circular bio-economy concepts.

Why Are Algal Trees Important?

• Low CO_2 Emissions

Research and pilot production indicate that the microalgae are able to absorb carbon dioxide at a much higher rate than land-based plants, due to their fast growth and high photosynthetic efficiency. Several controlled studies report a single algae tree can capture the same amount of carbon as several mature trees.

• Space-Saving Technology

The urban cities have to deal with the problem of land restriction in plantation drives. Compared to other algae trees, algae trees can be installed at comparatively less space near traffic junctions, railway stations, bus terminal, industrial area, smart city corridors, educational campus etc. The algae-based systems, apart from CO_2 reduction, can potentially help to reduce the particulate pollutants locally like PM2.5 and PM10 as the air quality around the system is improved.

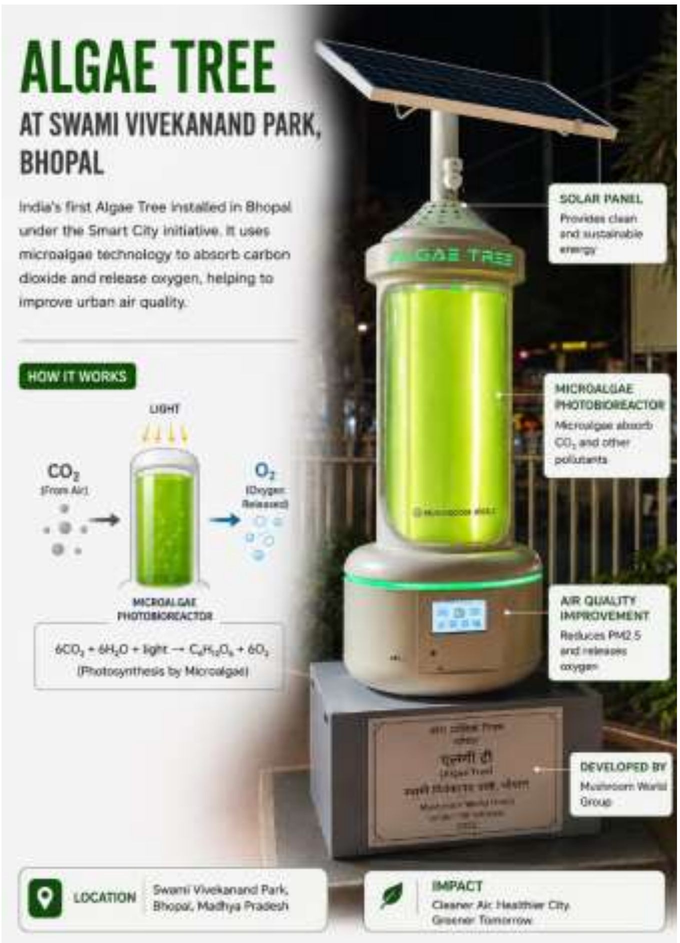
• Renewable and Sustainable

Algae trees are a sustainable green technology that can be implemented using solar energy and biological carbon capture, which fits well with the climate action objectives and carbon neutrality projects.

The first algae tree initiative in India

The algae tree technology has recently been installed in India in Bhopal, Madhya Pradesh. The technology is based on microalgae carbon capture technology with smart environmental monitoring and solar power. This project shows India's interest in the adoption of bio-inspired technologies for urban sustainability.

This technology has been suggested as an additional solution in much polluted urban areas where the establishment of large plantations is not possible. Experts say that algae trees need to be seen as complimentary to the natural forests and urban green, not as a replacement.



Agriculture entrepreneurship and startups are encouraged

Algae tree technology provides several avenues to young entrepreneurs, agricultural engineers, environmental startups, and researchers in India.

Potential Startup Areas

1. Urban carbon capture systems
2. Smart environmental monitoring
3. Algal biomass production
4. Biofertilizer manufacturing
5. Algae cultivation systems
6. Green infrastructure solutions
7. Smart city environmental services
8. Scope for Agricultural Engineers

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Agricultural Structure and Process Engineering students and professionals can help in:

1. Photobioreactor design
2. Fluid flow and aeration systems
3. Solar-powered automation
4. IoT-based monitoring systems
5. Biomass harvesting technologies
6. Sustainable environmental engineering
7. Integration with Circular Economy

Harvested algal biomass may be converted into value-added products such as

1. Organic fertilizers
2. Biochar
3. Biogas
4. Biofuel feedstock
5. Aquaculture feed supplements

This generates extra pollution control benefits as well as economic benefits.

Algae Trees have the following challenges:

Although the algae tree systems have great potential, there are a number of challenges that include high initial installation cost, regular maintenance needs, requirement for controlled environmental conditions, technical expertise in cultivating algae, energy usage for pumping and circulation, and public awareness and acceptance. More research is needed to enhance efficiency, operational cost reduction and field performance in long-term usage in Indian climatic conditions.

Future Prospects

Algae tree technology seems very promising for the future, particularly in fast-growing urbanized nations like India. Implementing Artificial Intelligence (AI), Internet of Things (IoT), renewable energy systems, and smart city infrastructure. Algae used for urban purification can be made very economically viable with the help of carbon credit mechanisms. Indigenous algal tree systems can be developed by research institutions, engineering universities, startups and also the municipal authorities for India, which would be cost-effective based on the Indian environments.

Conclusion

Algae tree technology is an innovative combination of biology, engineering and sustainability that is capable of reducing urban pollution and climate change. Natural forests are irreplaceable, but in overcrowded urban areas where natural plantations are hard to establish, algae trees can be used as tools for the environment. Their carbon-dioxide capturing capacity, their ability to improve local air quality and their production of valuable biomass, shows their vast potential in achieving sustainable urban development and agripreneurship in India. As the world increasingly turns to smart cities, renewable energy and carbon neutrality, algae trees could play a crucial part in the environmental infrastructure of the future. There are plenty of opportunities for agricultural engineers, researchers, and young entrepreneurs to be part of this new and rapidly expanding green technology field.

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Importance of Social Intelligence in Different Disciplines

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In today's interconnected world, success in any field depends not only on technical knowledge but also on the ability to understand and relate to people. This ability, known as social intelligence, plays a crucial role across diverse disciplines from agriculture and education to business, technology, and media. It helps individuals communicate effectively, build trust, manage conflicts, and create meaningful relationships. By enhancing collaboration and understanding, social intelligence becomes a key driver of professional effectiveness and societal progress.

Agricultural Extension

1. Effective communication with farmers

Clear communication helps extension workers share agricultural knowledge, technology, and practices effectively. It ensures farmers understand recommendations and can implement them properly.

Example: An extension officer uses local language and visual aids to explain the benefits of drip irrigation to illiterate farmers, ensuring they understand the concept fully.

2. Understanding Social and Cultural Contexts

Extension work must consider farmers traditions, beliefs and cultural practices to gain acceptance for new technologies.

Example: Before promoting mechanized farming, the officer respects local customs around sowing dates and explains how technology aligns with those traditions.

3. Building Relationships and Trust

Trust is crucial for farmers to adopt new practices. Building long-term relationships helps extension workers gain credibility.

Example: An officer regularly visits farmers, listens to their challenges and offers practical solutions leading farmers to trust his advice on pest control.

4. Encouraging Behaviour Change

The goal of extension is to influence farmers practices for better productivity and sustainability.

Example: A campaign on integrated pest management encourages farmers to reduce pesticide use by showing success stories from neighbouring villages.

5. Leadership and Teamwork

Extension workers need leadership skills to guide farmer groups and teamwork skills to collaborate with other agencies and stakeholders.

Example: An officer forms a Farmer Producer Organization (FPO) and trains its leaders to collectively market their produce, improving profits.

Education

1. Student Engagement: Teachers with high Social Intelligence understand students emotions, learning styles and social dynamics, which helps create inclusive and interactive classrooms.

Example: A teacher notices a shy student avoiding group activities. By gently encouraging participation and pairing the student with supportive peers, the teacher increases engagement and confidence.

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2. Conflict Resolution: Social Intelligence allows teachers to mediate student disputes calmly, fostering collaboration and reducing classroom tension.

Example: When two students argue over shared resources, the teacher listens to both sides, validates feelings, and suggests a fair turn-taking system, preventing escalation.

3. Parental Communication: Effective interaction with parents builds trust and strengthens the home-school connection, improving student outcomes.

Example: A teacher observes a student struggling academically and organizes a meeting with the parents to discuss challenges and suggest home strategies, leading to improved performance.

Business And Management

1. Leadership: Socially intelligent leaders understand team members emotions, inspire motivation and manage diverse teams effectively.

Example: A manager notices that an employee is stressed about deadlines. Instead of pressuring the manager redistributes tasks and offers support, maintaining morale and productivity.

2. Negotiation and Sales: Social Intelligence helps professionals read clients emotions, adapt communication styles and close deals effectively.

Example: During a sales pitch, the client seems hesitant. The sales person uses empathy, asks about concerns and offers a flexible payment plan, successfully securing the deal.

3. Teamwork: Social Intelligence fosters trust among team members, reduces conflicts and improves overall collaboration.

Example: In a project meeting, two employees disagree on strategy. The team leader listens to both, finds common ground and creates a combined approach, ensuring cooperation.

Information Technology

1. Team Collaboration: Software development involves multiple roles like programmers, designers, and clients; effective communication and coordination are essential for success.

Example: In a mobile app project, developers hold regular meetings with designers and clients to ensure the app's features meet user expectations and deadlines.

2. User-Centered Design: Developers must think from the user's perspective to create systems that are easy to navigate and meet real needs.

Example: While designing a banking app, developers include a simple interface and large icons after understanding that many users are older adults with limited tech skills.

3. Tech Support: Providing technical support requires patience, empathy and clear communication to solve user's problems effectively.

Example: A support agent assists a frustrated customer by calmly explaining how to reset their email password, guiding step-by-step without using technical jargon.

Media And Communication

1. Audience Engagement - This means understanding what your audience cares about what they like, feel and think so that the media content connects with them emotionally or intellectually.

Example: A Youtuber creating content for teenagers might use humour, music trends or relatable school stories to keep them engaged.

2. Conflict Sensitivity - Media professionals must handle topics like violence, politics or disasters carefully to avoid hurting people's emotions or escalating tensions.

Example: While covering a protest, a journalist avoids using inflammatory language and instead focuses on facts and voices from both sides.

3. Interviewing - When conducting interviews, it's important to observe body language, facial expressions, and tone of voice to fully understand what the person is saying (or not saying).

Example: A reporter interviewing a grieving family member speaks softly, listens patiently, and notes if the person's voice trembles or if they pause, showing signs of deep emotion.

Social intelligence is a powerful skill that enhances performance across all disciplines by improving communication, empathy, and teamwork. Whether it is guiding farmers, teaching students, leading organizations, developing technology, or engaging audiences, the ability to understand people makes a significant difference. In a world driven by human interaction, social intelligence is not just an added advantage, it is essential for success and sustainable development.

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Closing the Metabolic Loop: Precision Engineering of Nutrient Cycling in Multi-Spatial Integrated Multi-Trophic Aquaculture (IMTA) Systems

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Traditional intensive aquaculture systems face significant sustainability challenges due to the heavy discharge of nitrogenous and phosphorus-rich effluents. Integrated Multi-Trophic Aquaculture (IMTA) offers a circular bio-economy solution by utilizing the waste of fed species as nutritional inputs for extractive organisms. However, achieving peak ecological efficiency requires moving beyond simple multi-species co-culture toward precision spatial engineering. This article evaluates the multi-spatial dynamics of nitrogen (N) and phosphorus (P) cycling across pelagic and benthic niches. By mathematically balancing the biomass ratios of finfish, particulate-extractive bivalves and dissolved-nutrient-extractive seaweeds, modern IMTA can achieve a near zero-waste metabolic loop, significantly reducing environmental eutrophication while maximizing economic output.

1. Introduction

The rapid expansion of global aquaculture has triggered critical environmental concerns, particularly regarding benthic loading and the eutrophication of receiving water bodies. Intensive fed aquaculture, such as cage and tank culture of fin fish, releases vast amounts of metabolic waste. Approximately 60%-70% of the nitrogen and phosphorus administered via commercial feeds is lost to the surrounding environment as uneaten food, feaces and excretory products (Chopin et al., 2001).

Integrated Multi-Trophic Aquaculture (IMTA) addresses this by mimicking natural ecosystem structures. By pairing "fed" species (e.g., finfish) with "extractive" species that utilize organic particulate waste (e.g., bivalves, sea cucumbers) and dissolved inorganic nutrients (e.g., macroalgae), IMTA converts potential pollutants into high-value secondary commercial products. However, commercializing IMTA has historically suffered from poorly managed nutrient capture. This article explores how precision multi-spatial engineering the deliberate, measured positioning of trophic levels across vertical and horizontal planes can close the metabolic loop to achieve a highly efficient, zero-waste system.

2. Multi-Spatial Biogeochemical Cycling

To optimize an IMTA system, the waste stream must be mapped across distinct spatial dimensions, matching the physical behaviour of nutrients with the physiological traits of extractive species.

2.1 The Pelagic/Sessile Dimension: Dissolved Inorganic Nutrients

Fin fish excrete the majority of their nitrogenous waste directly into the water column as dissolved inorganic nitrogen (DIN), primarily in the form of ammonia (NH_4+). This highly soluble fraction is highly bioavailable to macroalgae (seaweeds) positioned downstream in the pelagic zone.

Macroalgae function as open-water biofilters. Cultivating fast-growing species like Ulva or Gracilaria in the immediate path of the hydrodynamic plume ensures rapid assimilation of NH_4+ and dissolved phosphorus via cellular active transport mechanisms (Neori et al., 2004). This spatial placement relies heavily on local current velocities; if water movement is too fast, contact time is

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insufficient, whereas stagnant waters lead to nutrient depletion zones.

2.2 The Mid-Water Dimension: Particulate Organic Matter

Sinking particulate organic matter (POM) consists of uneaten feed pellets and heavier faecal fractions. This waste stream is split by particle size:

Fine suspended particulates (<100 µm): These remain buoyant in the mid-water column and are ideal inputs for filter-feeding bivalves (e.g., mussels, oysters) suspended on longlines or rafts adjacent to fish cages (Reid et al., 2009).

Heavy settleable solids (>100 µm): These rapidly sink toward the seafloor, bypassing pelagic extractors entirely.

2.3 The Benthic Dimension: Settleable Solids

The solid waste that escapes mid-water capture accumulates on the substrate, creating a localized organic loading zone. Left unmanaged, this induces hypoxic conditions in the sediment due to microbial decomposition. Precision IMTA counters this by introducing benthic deposit feeders, such as sea cucumbers (*Apostichopus japonicus*) or epibenthic detritivores. These organisms ingest the heavy faecal matter and bioturbate the sediment, converting organic carbon into biomass while maintaining aerobic conditions in the upper sediment layers (Tolon et al., 2017).

3. Precision Engineering: Stoichiometric Balancing

The core failure of early IMTA setups was arbitrary species stocking, which led to nutrient bypass or extractive crop starvation. Precision engineering requires strict stoichiometric balancing, where the aggregate nutrient output of the fed species matches the uptake kinetics of the extractive biomass.

Trophic Layer	Target Waste Fraction	Representative Species	Key Metabolic Function
Fed Layer	Nutrient Input (Feed)	Carnivorous/Omnivorous Fish	Primary biomass and nutrient source
Pelagic Extractive	Dissolved Inorganic Nutrients (NH_4+, PO_4^{3-})	Gracilaria spp., Saccharina latissima	Photosynthetic assimilation of dissolved nutrients
Mid-Water Extractive	Fine Suspended Particulate Organic Matter (<100 µm)	Mussels (Mytilus edulis), Oysters	Mechanical filtration of suspended organic particles
Benthic Extractive	Heavy Settleable Particulate Organic Matter (>100 µm)	Sea cucumbers (Apostichopus japonicus), Polychaetes	Detrital consumption and sediment bioturbation/aeration

To calculate the exact biomass ratios, engineers utilize the specific ingestion and excretion rates of the fed species. For example, if 1,000 kg of fish feed yields a net loss of 50kg of dissolved nitrogen and the target macroalgae has a known nitrogen assimilation capacity of 2kg N per kg of wet weight per season, the required seaweed cultivation area can be calculated precisely to match the plume volume (Whitmore et al., 2022).

Furthermore, hydrodynamics plays a non-negotiable role. 3D acoustic Doppler current profilers (ADCP) are deployed to map the directional velocity of the

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effluent plume, allowing spatial configurations to adapt dynamically to seasonal current shifts.

4. Challenges in Scaling to Zero-Waste Models

While conceptually flawless, scaling a multi-spatial IMTA system to achieve an absolute zero-waste loop presents operational hurdles:

Hydrodynamic Unpredictability: In open-ocean environments, shifting currents can carry dissolved nutrients away from the seaweed lines, breaking the spatial link between source and sink.

Biosecurity Risks: Polyculture systems risk acting as horizontal vector pathways for pathogens. If a disease breaks out in the finfish stocks, suspended bivalves can bioaccumulate the viral or bacterial particles, complicating biosecurity management.

Market Synchronization: Aligning the harvesting cycles of three distinct cash crops (e.g., fish, mussels, seaweed) requires highly complex farm management and diverse supply chain logistics.

5. Conclusion

Precision-engineered IMTA represents a profound shift from traditional monoculture toward circular ecosystem engineering. By mathematically and spatially aligning extractive species with pelagic, mid-water and benthic waste trajectories, aquaculture operations can drastically minimize their environmental footprint. Closing the metabolic loop not only mitigates the risks of coastal eutrophication but also enhances resource-use efficiency, turning metabolic waste into economic resilience.

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Mushroom based nutraceuticals and functional foods; development, health, benefits and market potential

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Mushrooms are gaining worldwide importance as functional foods and nutraceuticals due to their high nutritional value and wide range of health-promoting bioactive compounds. They are rich in proteins, dietary fibre, vitamins, minerals, polysaccharides, terpenes, antioxidants and β-glucans, which contribute to various therapeutic properties such as antioxidant, antimicrobial, anti-inflammatory, anticancer, antidiabetic and immunomodulatory activities. Traditional medicinal systems in countries such as China, Japan and India have long recognized the medicinal importance of edible mushrooms, and modern scientific research has further validated their potential in promoting human health and preventing chronic diseases. Mushroom-derived compounds are increasingly being incorporated into functional foods, dietary supplements, beverages, meat alternatives and nutraceutical products to enhance nutritional quality and sustainability. Advanced production techniques including solid-state fermentation and submerged fermentation have improved the large-scale production of mushroom biomass and bioactive metabolites. In addition, mushroom-based products show promising applications in gut health, cardiovascular health, metabolic regulation and immune support. Growing consumer preference for natural and sustainable food ingredients has expanded the global market potential of mushroom-derived products. However, challenges such as standardization, shelf-life improvement, regulatory approval and validation through human clinical studies still remain. Overall, mushrooms and mycelia represent a sustainable and innovative resource for the development of future functional foods and nutraceuticals with significant health, economic and environmental benefits.

Introduction

Mushrooms, the visible fruiting bodies of fungi, have long played an important role in both nature and human diets. Today, they are valued as a low-calorie, nutrient-rich food, providing proteins, dietary fiber, minerals and essential vitamins such as vitamin D, selenium and B-complex vitamins nutrients often limited in plant-based diets. With growing awareness of health and wellness, the demand for functional foods, foods that offer benefits beyond basic nutrition has increased significantly. Mushrooms are emerging as a key player in this space. Though thousands of species exist, only a few are widely cultivated, prized for their rich nutritional and bioactive profile. They contain compounds such as β-glucans, polyphenols, terpenoids, and polysaccharides, which are linked to immune support, anti-inflammatory effects, blood sugar regulation and potential disease prevention (Ustun *et al.,* 2018). Their natural composition also allows better absorption in the human body, making them valuable nutraceutical ingredients. Today, mushrooms are used in a wide range of products, including baked goods, dairy alternatives, meat substitutes, beverages, and health supplements, enhancing both nutrition and sustainability. To meet rising demand, advanced production techniques like solid-state fermentation (SSF) and submerged fermentation (SmF) are being used to efficiently produce mushroom biomass and bioactive compounds, improving consistency and scalability. Mushrooms also have a rich cultural and historical background. Ancient civilizations such as Egypt, Greece, China, and India recognized their food and medicinal value. Over time, global acceptance has grown, supported by scientific research and evolving food trends. Cultivation practices, which began as early as 600 CE in China and later expanded commercially with species like *Agaricus bisporus*, have now become more advanced and sustainable. Despite growing research, gaps remain in understanding how environmental, genetic and metabolic factors influence bioactive compound production. Further work is needed to standardize mushroom-based products, improve shelf life and validate their health benefits. Overall, mushrooms have evolved from traditional remedies to modern functional foods, offering immense potential for health, sustainability, and future innovation in the global food industry.

Nutraceuticals - bioactive compounds of mushrooms

For many years, traditional Asian cultures especially in China, Japan, Korea, and India have used edible mushrooms as natural remedies for various diseases. Today, mushrooms contain special bioactive compounds that can help protect against tumors, infections and viruses, and also help in lowering cholesterol levels. Mushrooms are rich in important natural substances like polysaccharides, proteins, terpenes, and glycoproteins. These "wonder compounds" play a key role in promoting health. Because of these benefits, mushrooms are often seen as a "magic food" that can help improve overall health and well-being (Ustun *et al.,* 2018, Das *et al.,* 2021, Keservani *et al.,* 2010).

Polysaccharides

Mushrooms are rich in powerful natural compounds that offer many health benefits. Oyster mushrooms contain substances like polysaccharides and natural statins that can help lower cholesterol levels. Some mushrooms, such as *Agaricus blazei*, have compounds that strengthen the immune system and may help in managing cancer and immune-related diseases (Ustun *et al.,* 2018). Common mushrooms like *Agaricus bisporus* (button mushroom) also contain compounds that may help slow the growth of breast cancer cells. Different types of mushrooms produce special substances such as pleuran (Yang *et al.,* 2025), lentinan, and ganoderan, which are forms of beta-glucans known for their health-promoting effects. Certain mushrooms like *Hericium erinaceus* (lion's mane) may also help reduce fatigue, making them useful in areas like sports nutrition. These mushroom compounds can act as antioxidants, fight viruses, reduce inflammation, support immunity and help protect against cancer (Sharma *et al.,* 2014) making mushrooms an important part of a healthy diet.

Protein

Mushrooms contain special proteins and peptides that offer important health benefits and have strong potential in medicine. These include compounds like lectins, immunomodulatory proteins, and antimicrobial proteins, which help protect the body and support overall health. Among them, lectins are particularly important. They can bind to specific substances on cell surfaces and have been shown to help control the growth of harmful cells, including cancer cells, while also boosting the immune system. Lectins found in common mushrooms like *Agaricus bisporus* (button mushroom) and *Ganoderma lucidum* are especially well studied for their anti-cancer and immune-supporting properties. Another advantage is that these lectin proteins remain stable even after heating, freezing, or other processing methods. This makes them useful ingredients in functional foods and nutraceutical products designed to support health and immunity (de Aguiar *et al.,* 26, Ustun *et al.,* 2018, Łysakowska *et al.,* 2023).

Terpenes

Terpenes are natural compounds found in mushrooms that give them their aroma and also provide many health benefits. These compounds have strong anti-inflammatory properties and are known for a wide range of medicinal effects, including anticancer, antiviral, antibacterial, and even antimalarial activities. Different types of terpenes, such as monoterpenes, sesquiterpenes and triterpenes, are found in various mushrooms. For example, special terpenes have been identified in mushrooms like *Pleurotus*, *Flammulina*, and *Ganoderma*. Because of their powerful biological activities, these compounds are being studied for use in developing medicines, especially for conditions like Alzheimer's disease and other degenerative disorders. Terpenes add to the value of mushrooms as a natural source of health-promoting and potentially therapeutic compounds (Ustun *et al.,* 2018, Łysakowska *et al.,* 2023).

Antioxidants

Antioxidants are important compounds that protect our body from damage caused by harmful molecules, which are linked to aging and diseases like diabetes, heart disease, cancer, and liver problems. Mushrooms are a good source of natural antioxidants. They contain important minerals like selenium and zinc, along with beneficial compounds such as ergothioneine, beta-glucans, phenolics, and flavonoids. These substances help boost the immune system, reduce cholesterol, fight viruses and may even support the body during treatments like chemotherapy and radiotherapy. Many well-known mushrooms, such as oyster mushrooms (*Pleurotus*), button mushrooms (*Agaricus*), reishi (*Ganoderma lucidum*), and shiitake (*Lentinula edodes*), are especially rich in antioxidants. Other mushrooms like *Hericium erinaceus* and *Cordyceps sinensis* are also valued for their antioxidant properties and are widely used in health supplements (Ustun *et al.,* 2018). Mushrooms act as natural protectors, helping the body stay healthy and fight against diseases.

Other nutraceutical compounds present in mushrooms

Mushrooms contain a wide range of natural compounds such as beta-glucans, dietary fiber, lectins, flavonoids, and vitamins. These bioactive substances are responsible for many of their health benefits. Because of these compounds, mushrooms can help protect the body in many ways. They may support heart, liver, and brain health, help fight infections, control blood sugar, and even reduce the risk of cancer. Some special mushrooms offer unique benefits. *Cordyceps militaris* helps boost the immune system and may support cancer treatment. *Hericium erinaceus* (lion's mane) is known for improving brain health and memory and is also used to support digestion and immunity. Other mushrooms like *Dictyophora indusiata* may help in nerve health, while *Panellus serotinus* can support liver health. Mushrooms such as oyster (*Pleurotus*), shiitake (*Lentinula edodes*), and button mushroom (*Agaricus bisporus*) also act as prebiotics, helping improve gut health (Ustun *et al.,* 2018). Mushrooms are powerful natural foods that promote better health and well-being in many ways.

Novel mushroom-derived products

Functional foods are natural or specially prepared foods that we eat daily to improve health and help prevent diseases. Nutraceuticals are food-based products like extracts, capsules, or tablets that provide medical or health benefits. Mushrooms can be eaten as regular food, taken as dietary supplements, or used as nutraceuticals, often called "mushroom-based health products". Mushroom nutraceuticals are usually made from extracts or dried forms of the mushroom (either the fruiting body or mycelium) (Ustun *et al.,* 2018). These are commonly available as capsules or tablets and are known to boost the immune system and improve the body's resistance to diseases. Mushrooms combine traditional knowledge with modern science, as they have been used for centuries and are now widely studied for their health benefits. Their bioactive compounds can be concentrated and used in supplement form. Since wild mushrooms are limited and expensive, most edible mushrooms today are cultivated on a large scale to meet demand.

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Mushrooms and their products are widely consumed either as fresh food or as dietary supplements, making them an important part of a healthy lifestyle.

Functional foods development

Functional foods can be consumed not only in their natural state, but also after biotechnical modification. These foods will enrich a healthy diet and improve the nutritional value of other food stuffs. In Table 1 below shows some of the functional foods derived from various mushrooms. By the production of these products, it was aimed to get high nutritional value, high-fibre and low-calorie novel functional foods and beverages having some functionalities such as improving the pasting properties of wheat flour, getting and increasing antioxidant, antimicrobial, antithrombotic and hypocholesterolaemia properties, decreasing the potential glycemic response, inhibition of food contaminants, avoiding food deterioration and protection from lipid peroxidation(Ustun *et al.,* 2018).

Mushroom species	Functional food
Agaricus aegerita	Cream cheese
Agrocybe aegerita	Snack food
Auricularia auricula	Bread
Agaricus bisporus	Snack food, Bread, Sponge cake
Agaricus blazei	Yoghurt Milk
Agaricus bohusii	Cream cheese
Boletus aereus	Pork meat produc
Boletus edulis	Beef burger
Cordyceps militaris	Extruded product
Laetiporus sulphureus	Chicken pate
Lentinula edodes	Baked food, Noodle, Frying batter
Pleurotus sajor-caju	Papad (An Indian snack food)
Schizophyllum commune	Cheese-like food
Suillus luteus and Coprinopsis atramentaria	Cottage cheese
Tirmania pinoyi	Soup

Table 1:

Nutraceuticals compounds development

Mushrooms are rich in important nutraceuticals such as healthy fats, vitamins (like vitamin C and E), proteins, amino acids, and carbohydrates especially beneficial polysaccharides. These nutrients play a key role in supporting overall health. For centuries, medicinal mushrooms have been used in countries like China and Japan and today their health benefits are also widely recognized around the world. Many mushrooms, including *Agaricus*, *Ganoderma*, *Lentinula*, and *Pleurotus*, contain special compounds that have been developed into health products. These mushroom compounds offer a wide range of benefits. They may help fight cancer, control blood sugar, reduce inflammation, and protect against infections. They are also useful in supporting heart health and managing conditions like high blood pressure. Mushroom-based products are available in many forms such as powders, extracts, capsules, and tablets. They can be made from different parts of the mushroom, including the fruiting body, mycelium, or spores. Some well-known medicinal mushrooms like *Cordyceps militaris*, *Hericium erinaceus* (lion's mane), and *Ganoderma lucidum* (reishi) have been widely studied for their health benefits. Many companies around the world produce mushroom-based supplements and health products. However, the way mushrooms are processed such as heating or drying can affect their effectiveness. Mushrooms are a valuable natural source of nutraceuticals and are increasingly used in modern health products to support a healthy lifestyle (Ustun *et al.,* 2018). In Table 2 below show some of the mushroom-based nutraceuticals and dietary supplements available in the market and their health claims (Yang *et al.,* 2025, Ustun *et al.,* 2018).

Mushroom species	Product in the market	Health benefit claim
Agaricus blazei	Agaricus blazie capsule	Immune support supplement
Agaricus blazei, Cordyceps sinensis, Coriolus versicolor, Ganoderma lucidum, Grifola frondosa and Lentinula edodes	Immune Assist complete	Immunity supporter
Agaricus blazei, Cordyceps sinensis, Ganoderma lucidum and Lentinula edodes	CocoaMojo-cocoa powder	Immunity supporter
Agaricus blazei, Ganoderma Lucidum, Grifola frondosa, Lentinula edodes and Pleurotus ostreatus	Agarikon.1	Enhancement of immune system
Cordyceps sinensis	Mycoformulas Endurance	Enhancement of intracellular energy exchange.
Cordyceps sinensis and Ganoderma lucidum	Nutricafe-organic performance coffee	Increases physical endurance and helps to remove toxins from your body
Cordyceps sinensis, Ganoderma lucidum, Hericium erinaceus and Inonotus obliquus	Mushroom Plus	Combines some of the most popular mushrooms for an overall health boost by supporting immune system, energy levels, and cognition
Ganoderma lucidum	Pure Red Reishi - capsules Organic Reishi tablets - MRL GanoSuper - concentrated extracts for coffee	Increases the body's resistance to stress and helps it overcome all health challenges more quickly, supports the body's normal cellular immune system
Ganoderma lucidum and Lentinula edodes	Organic ReiShi-Gen (synergestic formulations)	Immune support supplement

ISSN: 3049-2289

Grifola frondosa	MaitakeGold	Providing daily immune protection
Grifola frondosa and Lentinula edodes	OsteoMykon	Maintenance of bone health (indicated for osteoporosis)
Grifola frondosa and Phellinus linteus	Breast-Mate	Supports healthy breast tissue
Hericium erinaceus	MycoFormulas Memory	Memory support and daily mental clarity
Lentinula edodes	Shiitake gold - capsules	For complete physical health
Pleurotus ostreatus	Imunoglukan P4H capsules	Immune system enhancement
Trametes versicolor	ORIVEDA PSP-50	Immune supporter

Beneficial effects of diets incorporating mushroom – based formulation

Mushrooms can be used in fermentation and acts as the fermenting agent, breaking down raw materials and turning them into a nutrient-rich mass (called mycelial biomass) packed with natural compounds like polysaccharides, proteins, and other beneficial molecules. Mushroom extracts are used as the starting material for fermentation. during this process, the original compounds are transformed into new, smaller, and often more active substances such as amino acids, peptides, natural sugars, organic acids, and modified bioactive compounds. these changes can make the nutrients easier for the body to absorb and use.

1. Helps control blood pressure

Fermented mushroom products may support heart health by relaxing blood vessels, improving blood flow, and helping regulate cholesterol levels. they can also enhance the function of the inner lining of blood vessels.

2. Supports blood sugar balance

They may help manage blood sugar by slowing down carbohydrate digestion, improving insulin activity, and helping the body use glucose more effectively.

3. Improves gut health

Fermented mushroom compounds can encourage the growth of good gut bacteria and promote the production of beneficial substances like short-chain fatty acids, which are important for digestion and overall health.

4. Provides whole-body protection

These products may act as antioxidants, helping to neutralize harmful free radicals. they can also reduce inflammation, support the immune system, and show potential antimicrobial effects against harmful microbes (Lorena Vieira Bentolila de Aguiar *et al.,* 2026).

Markets potential of mushroom – future thrust

Mycoproteins, which are proteins derived from fungi, are still largely overlooked compared to animal-based proteins, even though they offer

ISSN: 3049-2289

significant potential. Unlike traditional protein sources, mycoproteins are not only nutritious but also have unique properties that help improve the texture and stability of foods, making them useful in both solid products like meat alternatives and liquid formulations such as beverages. The mushroom industry itself is steadily growing, valued at around US$18 million in 2023 (de Aguiar *et al.,* 2026) and expected to expand at a healthy rate in the coming years. This growth is closely linked to the rising demand for functional foods and nutraceuticals products that provide added health benefits beyond basic nutrition. At the same time, the alternative protein sector is gaining strong momentum. Fermentation-based protein production alone attracted over US$500 million in investments in 2023 (de Aguiar *et al.,* 2026), reflecting increasing global interest and innovation, with many companies exploring different fermentation technologies.

A key component in this space is mycelium, the root-like structure of fungi, which can be used to create a wide variety of food products. Its effectiveness depends on how it is grown and processed, and current research focuses on enhancing flavor (especially the savory "umami" taste), producing beneficial bioactive compounds, and reducing unwanted substances. Fermentation plays an important role here, as it can naturally improve nutritional quality by breaking down harmful or indigestible components. Another important trend is the use of mushrooms as natural sources of antioxidants, which help protect the body from damage caused by oxidative stress. Mushroom extracts are increasingly being added to foods or used as dietary supplements, driven by consumer preference for natural ingredients over synthetic ones. Additionally, mushrooms have an advantage over other protein sources because they can be produced quickly and efficiently. The future of mushroom-based foods may lie in personalized nutrition. Scientists are exploring how these ingredients can be combined with nutrigenomics the study of how food interacts with our genes to develop foods that support health and help prevent disease. As demand for such functional and preventive foods grows, it is expected to drive further research and innovation in this field. There are still challenges to overcome. These include concerns about heavy metal contamination, limited human studies to confirm health benefits, high production costs, lack of standardization, strict regulatory requirements, and some hesitation among consumers to adopt new food technologies (de Aguiar *et al.,* 2026). Despite these barriers, mycoproteins hold strong promise as a sustainable and health-focused solution for the future of food.

Conclusion

Edible mushrooms and their root-like structures (mycelia) are gaining attention as powerful ingredients for the future of food. They combine good nutrition with advanced food technology, making them ideal for developing functional foods, foods that not only nourish but also support health. Mushrooms are rich in protein, fibre, vitamins, minerals, and special compounds like beta-glucans, all of which contribute to a balanced and healthy diet. Research suggests that mushrooms may help improve gut health, reduce inflammation, support metabolism, and protect the body through antioxidant activity. These benefits highlight their potential as nutraceutical ingredients. However, scientists still need more human studies to fully confirm these health effects. Beyond nutrition, mushrooms and mycelia can also be used to produce high-value compounds such as proteins, enzymes, vitamins, and other bioactive substances. This makes them a flexible and sustainable option for creating next-generation foods. Mushroom-based products are likely to become a regular part of everyday diets. As production increases, they are expected to become more affordable while also remaining environmentally friendly, offering a smart solution for healthier and more sustainable eating

ISSN: 3049-2289

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Calcium and Magnesium: Factors Affecting Their Availability in Soils

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Calcium (Ca) and Magnesium (Mg) are essential secondary macronutrients that play fundamental roles in soil fertility, plant nutrition, and sustainable agricultural productivity *(Brady & Weil, 2016; Havlin et al., 2017)*. Calcium is crucial for cell wall formation, membrane stability, root development, and soil structural improvement, whereas magnesium is the central component of chlorophyll and a key activator of enzymes involved in photosynthesis, respiration, and nutrient metabolism *(Marschner, 2012)*. Although both nutrients may be abundant in many soils, their plant availability depends on multiple interacting factors including soil pH, parent material, texture, cation exchange capacity (CEC), organic matter, climatic conditions, leaching intensity, nutrient interactions, salinity, and management practices *(Mengel & Kirkby, 2001)*. Deficiencies of calcium and magnesium can significantly reduce crop yield and quality, especially in acidic, sandy, or heavily weathered soils *(Fageria, 2014)*.

Introduction

Calcium and magnesium are classified as secondary nutrients, yet their importance in plant growth and soil productivity is comparable to primary nutrients under many agricultural systems *(Havlin et al., 2017)*. Calcium is absorbed by plants as Ca^{2+} and contributes to structural functions, root elongation, and physiological stability *(Marschner, 2012)*. Magnesium, absorbed as Mg^{2+}, is necessary for chlorophyll synthesis and acts as a cofactor in many enzymatic reactions *(Mengel & Kirkby, 2001)*. Soil availability of these nutrients is highly dynamic and influenced by pedogenic processes, weathering, environmental conditions, and agronomic management *(Brady & Weil, 2016)*.

In many tropical and subtropical regions, especially high-rainfall areas, calcium and magnesium are often reduced through leaching, while in calcareous or alkaline soils, nutrient imbalance may reduce their effective uptake *(Fageria, 2014)*. Understanding the factors that govern Ca and Mg availability is therefore essential for maintaining balanced soil fertility, maximising crop productivity, and ensuring sustainable land management *(Havlin et al., 2017)*.

Roles of Calcium and Magnesium in Plants

Calcium (Ca)

Calcium (Ca) plays an essential role in maintaining plant growth, development, and soil health. It is an important component of calcium pectate, which strengthens plant cell walls and helps maintain the structural stability of plant tissues *(Marschner, 2012)*. Calcium also encourages active root growth and meristematic development, thereby supporting the proper formation of young tissues and improving the plant's ability to absorb water and nutrients from the soil *(Mengel & Kirkby, 2001)*. It also enhances membrane permeability and facilitates the movement and transport of nutrients within plant cells, which contributes to better physiological functioning *(Havlin et al., 2017)*. In soils, calcium helps reduce the toxic effects of elements such as aluminium, manganese, and sodium, particularly in acidic or saline conditions, thereby creating a more favourable environment for plant growth *(Fageria, 2014)*. Furthermore, calcium improves soil aggregation and structure by helping soil particles bind together, which enhances aeration, water infiltration, and overall soil fertility *(Brady & Weil, 2016)*.

ISSN: 3049-2289

Magnesium (Mg)

Magnesium (Mg) is an essential nutrient that plays a crucial role in plant growth and metabolic activities. It forms the central atom of the chlorophyll molecule and is therefore directly involved in the process of photosynthesis, which enables plants to produce food using sunlight *(Marschner, 2012)*. Magnesium also activates several enzymes that are involved in important physiological processes such as photosynthesis and respiration, thereby supporting efficient plant metabolism *(Mengel & Kirkby, 2001)*. In addition, it is essential for phosphate metabolism and ATP energy transfer, which are necessary for storing and supplying energy required for various biochemical reactions within the plant *(Havlin et al., 2017)*. Magnesium further supports protein synthesis and the translocation of carbohydrates from leaves to other plant parts, helping in proper growth and development *(Fageria, 2014)*. Moreover, adequate magnesium nutrition improves seed formation and enhances overall crop quality, contributing to better agricultural productivity *(Mengel & Kirkby, 2001)*.

Sources of Calcium and Magnesium in Soils

Calcium Sources

Calcite, dolomite, gypsum, and feldspars are important mineral sources of calcium in soils (Brady & Weil, 2016). Calcium is also present in exchangeable form on clay colloids and in the soil solution, making it available for plant uptake *(Havlin et al., 2017)*. In addition, agricultural amendments such as lime and gypsum are commonly applied to soils to supply supplemental calcium and improve soil fertility *(Fageria, 2014)*.

Magnesium Sources

Dolomite, biotite, hornblende, olivine, and serpentine are the major magnesium-bearing minerals commonly present in soils, and they act as the primary natural sources of magnesium through the process of mineral weathering *(Brady & Weil, 2016)*. Magnesium (Mg^{2+}) is also found in an exchangeable form on the surfaces of clay particles and organic colloids in the soil, which helps maintain its availability for absorption and utilisation by plant roots *(Havlin et al., 2017)*. Also, the magnesium content of soils is continuously restored through the natural weathering of minerals as well as through the application of magnesium-containing fertilisers, which are commonly used to improve soil fertility and support healthy plant growth *(Mengel & Kirkby, 2001)*.

Factors Affecting Calcium and Magnesium Availability in Soils

1. Soil pH

Soil pH strongly influences nutrient solubility and mobility *(Brady & Weil, 2016)*.

Acidic soils promote the leaching losses of calcium (Ca) and magnesium (Mg) from the soil profile because high rainfall and increased hydrogen ion concentration displace these nutrients from the soil exchange sites, causing them to be washed away more easily *(Fageria, 2014)*. Neutral soils generally provide the most favourable conditions for optimum nutrient availability, as essential nutrients remain

ISSN: 3049-2289

more balanced and accessible for plant uptake under such soil pH conditions *(Havlin et al., 2017)*. In contrast, alkaline soils may reduce magnesium uptake due to ionic imbalance and the precipitation of magnesium with carbonates, which decreases its solubility and availability to plants *(Mengel & Kirkby, 2001)*

2. Parent Material

The mineral composition of parent rock determines native reserves of Ca and Mg *(Brady & Weil, 2016).*

- Limestone and dolomite-derived soils are rich in Ca and Mg.
- Sandstone-derived soils are often deficient.
- Basaltic soils may contain substantial Mg reserves.

3. Soil Texture

Clay soils possess greater nutrient retention due to higher CEC, whereas sandy soils are more prone to leaching losses *(Havlin et al., 2017).*

4. Cation Exchange Capacity (CEC)

High CEC soils retain more exchangeable Ca^{2+} and Mg^{2+}, while low CEC soils lose nutrients rapidly *(Brady & Weil, 2016)*.

5. Organic Matter

Organic matter improves nutrient retention, moisture holding capacity, microbial activity, and pH buffering *(Havlin et al., 2017)*.

6. Rainfall and Leaching

Heavy rainfall accelerates nutrient loss and soil acidification in humid tropical soils *(Fageria, 2014).*

7. Nutrient Interactions

Excess potassium can suppress Mg uptake, while high ammonium levels may reduce Ca absorption *(Mengel & Kirkby, 2001)*.

8. Liming and Soil Amendments

Calcitic lime supplies calcium, whereas dolomitic lime supplies both calcium and magnesium *(Brady & Weil, 2016)*.

9. Soil Moisture and Drainage

Drought restricts nutrient diffusion, while water-logging reduces root activity and nutrient uptake *(Havlin et al., 2017)*.

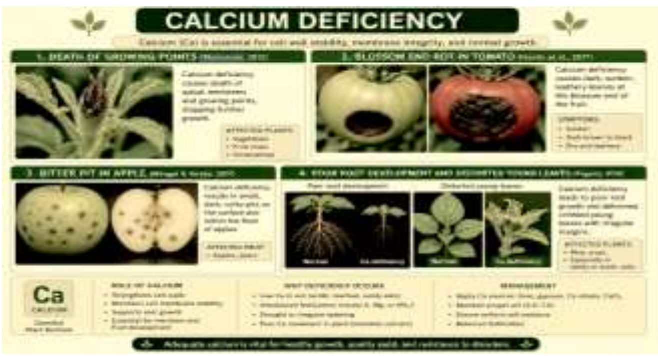
10. Cropping Intensity and Harvest Removal

Continuous cultivation without nutrient replenishment gradually depletes Ca and Mg reserves *(Fageria, 2014).*

Deficiency Symptoms

1.Calcium Deficiency

Calcium deficiency in plants leads to the death of growing points, particularly in the root and shoot tips, because calcium is essential for cell division and the development of meristematic tissues *(Marschner, 2012)*. One of the most common symptoms of calcium deficiency is blossom end rot in tomato, where dark, sunken lesions develop at the blossom end of the fruit due to inadequate calcium supply during fruit development *(Havlin et al., 2017)*. In apple, calcium deficiency causes bitter pit, a physiological disorder characterised by small, dark, sunken spots on the fruit surface that reduce fruit quality and storage life *(Mengel & Kirkby, 2001)*. Deficiency of calcium also results in poor root development and distortion of young leaves, as the nutrient plays a crucial role in maintaining cell wall strength and normal plant growth *(Fageria, 2014)*.



ISSN: 3049-2289

2.Magnesium Deficiency

Magnesium deficiency in plants commonly causes interveinal chlorosis in older leaves, where the areas between the veins turn yellow while the veins remain green, because magnesium is a mobile nutrient that is transferred from older to younger plant tissues during deficiency conditions *(Marschner, 2012)*. As the deficiency becomes more severe, the affected leaves show extensive yellowing followed by necrosis, leading to the death of leaf tissues and reduced plant vigour *(Mengel & Kirkby, 2001)*. Magnesium deficiency also reduces photosynthesis because magnesium is a central component of the chlorophyll molecule, and this ultimately results in poor grain filling and lower crop yield (*Havlin et al., 2017)*.

Management Practices to Improve Availability

Regular soil testing is necessary for balanced nutrient management because it helps determine the nutrient status of the soil and allows farmers to apply the correct amount of fertilisers required for optimum crop growth and productivity *(Havlin et al., 2017)*. In acidic soils which are deficient in magnesium, the application of dolomitic lime is recommended because it not only raises soil pH but also supplies magnesium to plants *(Brady & Weil, 2016)*. Gypsum application is useful in improving calcium deficiency, as it provides an available source of calcium without causing major changes in soil pH (Fageria, 2014). The addition of organic manures and compost improves soil health by enhancing soil structure, increasing water-holding capacity, and improving the soil's ability to retain and supply nutrients *(Mengel & Kirkby, 2001)*. Furthermore, balanced fertilisation practices and the avoidance of excessive potassium application help improve magnesium uptake by plants, since high levels of potassium can interfere with magnesium absorption *(Marschner, 2012)*.

Conclusion

Calcium and magnesium are essential secondary nutrients that play crucial roles in maintaining soil fertility, plant growth, and sustainable agricultural productivity. Calcium contributes to cell wall formation, root development, membrane stability, and soil structural improvement, while magnesium is essential for chlorophyll formation, photosynthesis, enzyme activation, and energy transfer within plants. The availability of these nutrients in soils is strongly influenced by several interacting factors such as soil pH, parent material, texture, cation exchange capacity, organic matter content, rainfall, leaching, nutrient interactions, and management practices.

Acidic and sandy soils are particularly prone to calcium and magnesium deficiencies due to nutrient leaching and low retention capacity. Excessive application of competing nutrients such as potassium and ammonium may further reduce their uptake by plants. Plant growth hormones indirectly support calcium and magnesium utilisation by enhancing root growth, nutrient transport, and stress tolerance. Therefore, maintaining balanced nutrient management is necessary for efficient absorption and utilisation of these nutrients.

Sustainable management practices such as liming, application of dolomitic amendments, incorporation of organic matter, balanced fertilisation, proper irrigation, and regular soil testing can significantly improve calcium and magnesium availability in soils. Understanding the factors affecting these nutrients not only helps in preventing deficiency disorders but

ISSN: 3049-2289

also contributes to improved crop yield, soil health, and long-term agricultural sustainability.

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Role of chelates in nutrient availability

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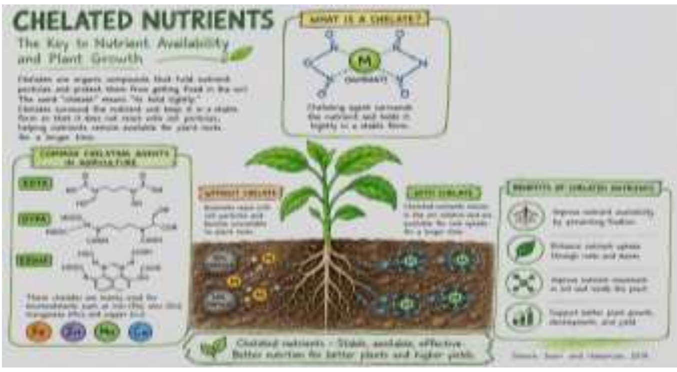
Chelates are special compounds that help keep nutrients available for plants in the soil. Many important micronutrients such as iron, zinc, manganese, and copper become unavailable in alkaline and calcareous soils because they get fixed with soil particles. Chelates protect these nutrients and help plants absorb them easily through roots and leaves. Chelated fertilisers improve nutrient use efficiency, plant growth, crop yield, and crop quality. They are also useful under stress conditions like drought and salinity where nutrient uptake becomes difficult. Different types of chelates such as EDTA, DTPA, EDDHA, and natural amino acid chelates are commonly used in agriculture. Although chelates have many benefits, excessive use of synthetic chelates may affect soil and water quality. Therefore, proper management and the use of eco-friendly chelates are important for sustainable agriculture. Chelates play a major role in modern farming by improving nutrient availability and supporting better crop production *(Souri and Hatamian, 2019; Hernández-Apaolaza et al., 2023).*

Introduction

Plants need nutrients for proper growth, healthy leaves, strong roots, flowering, and better crop yield. Along with major nutrients like nitrogen, phosphorus, and potassium, plants also need small amounts of micronutrients such as iron, zinc, manganese, and copper. Even though these nutrients are required in small quantities, they are very important for plant growth and development. In many soils, especially alkaline and calcareous soils, these micronutrients become locked in the soil and are not easily available to plants. When plants cannot absorb enough nutrients, deficiency symptoms appear, such as yellow leaves, weak growth, poor flowering, and reduced yield. Chelates help solve this problem by keeping nutrients available for plant uptake. Because of their ability to improve nutrient absorption and fertiliser efficiency, chelated fertilisers are widely used in modern agriculture *(Souri and Hatamian, 2019).*

What Are Chelates?

Chelates are special organic compounds that hold nutrient particles and protect them from getting fixed in the soil. The word "chelate" means "to hold tightly." Chelates surround the nutrient and keep it in a stable form so that it does not react with soil particles. This helps nutrients remain available for plant roots for a longer time. Common chelating agents used in agriculture are EDTA, DTPA, and EDDHA. These chelates are mainly used for micronutrients such as iron, zinc, manganese, and copper. Chelated nutrients can also be applied through foliar sprays because plants absorb them quickly through leaves. Chelates improve nutrient movement in soil and inside the plant, which supports better plant growth and development *(Souri and Hatamian, 2019).*



Role of Chelates in Nutrient Availability

Chelates play a very important role in helping plants absorb nutrients easily from the soil. In many soils, especially alkaline soils, micronutrients like iron,

ISSN: 3049-2289

zinc, manganese, and copper become locked in the soil after reacting with calcium and other soil materials. Chelates protect these nutrients and keep them in a soluble form that plants can absorb through their roots and leaves. They improve nutrient movement in soil and reduce nutrient loss caused by fixation and leaching. Chelated nutrients are absorbed faster and help improve photosynthesis, chlorophyll formation, enzyme activity, root growth, flowering, fruit quality, and crop yield. Chelates are also useful during drought, salinity, and other stress conditions because they help maintain nutrient supply even under unfavourable conditions. Because of these benefits, chelated fertilisers are widely used in fruits, vegetables, flowers, and field crops to improve plant health and increase agricultural production *(Hernández-Apaolaza et al., 2023).*

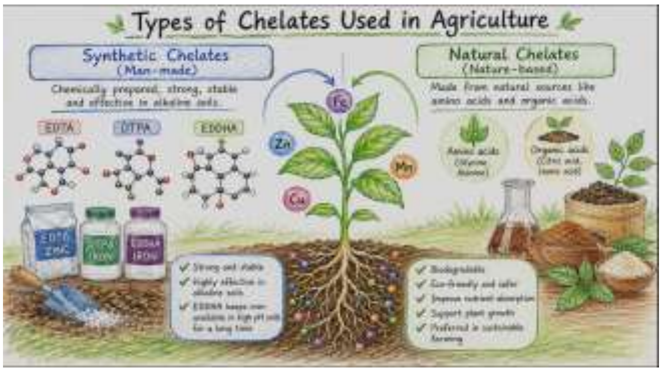
Types of Chelates

Chelates used in agriculture are mainly divided into synthetic chelates and natural chelates. Synthetic chelates are chemically prepared compounds such as EDTA, DTPA, and EDDHA. These chelates are strong, stable, and highly effective in alkaline soils. EDDHA is especially useful for iron fertilisers in high pH soils because it keeps iron available for a long time.

Natural chelates are made from natural substances like amino acids and organic acids. These chelates are biodegradable and considered safer for the environment. Natural chelates also improve nutrient absorption and support plant growth. Nowadays, many farmers prefer natural chelates because they are more eco-friendly and suitable for sustainable farming systems *(Hernández-Apaolaza et al., 2023).*

Advantages of Chelates

Chelates provide many advantages in agriculture. They improve nutrient availability and help plants absorb nutrients more efficiently. Chelated fertilisers reduce nutrient loss in soil and improve fertiliser use efficiency. They also help correct nutrient deficiency symptoms quickly, especially when applied as foliar sprays. Chelates improve plant growth, leaf colour, root development, flowering, fruit quality, and crop yield. They are highly useful in alkaline soils where normal micronutrient fertilisers do not work effectively. Chelates also help plants tolerate environmental stress conditions such as drought and salinity, which supports better crop production *(Souri and Hatamian, 2019).*



Limitations of Chelates

Although chelates are very useful, they also have some disadvantages. Synthetic chelates are more expensive than ordinary fertilisers, which increases the cost of crop production. Some synthetic chelates remain in soil for a long time and may affect soil and water quality if overused. Excess use of chelated fertilisers may also disturb nutrient balance in plants and soils. Therefore, farmers should use chelated fertilisers carefully and follow recommended doses for safe and effective nutrient management *(Mertens et al., 2018).*

Future Scope of Chelates

Scientists are now developing safer and more eco-friendly chelates for sustainable agriculture. Natural and biodegradable chelates are becoming more popular because they reduce environmental pollution and improve soil health. Research is also being done on nano-chelated fertilisers, which can supply nutrients more efficiently to plants. In the future, improved chelate technology can help farmers increase crop production while protecting soil and

ISSN: 3049-2289

environmental health *(Hernández-Apaolaza et al., 2023).*

Conclusion

Chelates play an important role in improving nutrient availability and fertiliser efficiency in agriculture. They protect nutrients from getting locked in the soil and help plants absorb them easily. Chelated fertilisers improve plant growth, crop yield, nutrient uptake, and crop quality. They are especially useful in alkaline and nutrient-deficient soils where micronutrient availability is low. Chelates also help plants grow better under stress conditions such as drought and salinity. Although synthetic chelates are costly, their benefits in improving crop production are very important. The development of natural and eco-friendly chelates can further support sustainable agriculture and future food production *(Souri and Hatamian, 2019; Hernández-Apaolaza et al., 2023).*

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Blending of Agricultural Themes in Bharatanatyam

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Introduction

Agriculture has long been the backbone of Indian economy. It plays a crucial role in shaping not only the economic and livelihood systems but also the cultural traditions and artistic expressions. Agricultural practices from land preparation, sowing, irrigation to harvesting are not simply economic activities but they are integral part of rural community life. Consequently, these agricultural realities have been reflected in literatures, music and performing arts highlighting the relationship between human and nature. Bharatanatyam, an indigenous classical dance form of India, serves as a powerful medium for conveying these everyday agricultural experiences through gestures, expressive movements and symbolic storytelling. While it is predominantly associated with devotional and mythological themes, Bharatanatyam also reflects agricultural themes (seasonal variation, crop growth, sowing, harvesting, etc) through symbolic gestures (Hastas) and Abhinaya (expression). Bharatanatyam translates agricultural realities into artistic expression, thereby preserving farming traditions and traditional knowledge.

This article examines the portrayal of agricultural themes in Bharatanatyam, highlighting the relationship between agricultural practices, agrarian lifestyle and cultural traditions.

Classical Text Connection

The theoretical framework for representing agrarian life in Bharatanatyam can be traced from Natyashastra by Bharta Muni, which defines drama as imitation of worldly life.

"Lokavruttanukaranam Natyam etad bhavisyati"

-Natya is the representation of ways of world.

The concept of Lokavrittam (worldly life) allows performance to reflect day to day activities and occupations. As Indian Society is largely agriculture oriented, farming activities, seasonal cycles and rural experiences are included in this representation.

Furthermore, the Rasa theory articulated by Natyashastra

"Vibhava-anubhava-vyabhicari-samyogad-rasa-nispattih"

Explains how emotions arise from specific situations and performer's expressions. This provides theoretical support for depiction of agrarian emotions like hope during sowing, joy of harvesting and sorrow during drought.

The Abinaya Darpana further strengthens the scope for representation of agrarian life by detailing the use of Angika (physical expression), Sattvika (expression of inner feelings) and Aharya (costume and jewels) abhinayas and various hand gestures (mudras). Although the text does not directly address agricultural themes, its structured system of gestures and expressions enables the symbolic depiction of natural elements and weather parameters, farming activities and rural emotions. Through this established expressive framework, Bharatanatyam gains ability to visually communicate Agricultural practices and allied activities and farmer's emotions.

ISSN: 3049-2289

Temple Roots And Devdasi Traditions

Originating in temples, Bharatanatyam was more than art- it was a devotional offering. Temples like those in Chidambaram, Thanjavur and Kumbakonam built in fertile regions hosted performances allied with agricultural festivals like Pongal, Aadi Perukku and Other festivals. Traditionally performed by Devdasis (dancer women, who generally dance only in temple courtyards offering their services to God), Bharatanatyam developed within temple institutions that were closely connected to the farming community. The temple rituals and festivals were often aligned with farming cycles including prayers for rain, soil fertility rituals and harvesting celebrations. Devdasis dance performances included composition praising deities associated with rainfall, Sun and Prosperity. Many dance items also portrayed the female leads or heroines in Bharatanatyam called the Nayikas waiting for their beloved one in the garden, set against the scenes of seasonal beauty and flowering landscapes, reflecting the richness of nature and agrarian life. Thus, temple traditions created a space where agricultural life and artistic expression came together, strengthening the depiction of agriculture in Bharatanatyam.

Margam And Its Symbolic Parallels With Agriculture

Margam meaning "path" or "way" in Tamil, refers to traditional performance sequence of items in Bharatanatyam. It is a structured progression that guides both the dancer and audience from an invocation to conclusion. This sequential arrangement can be analytically paralleled with agricultural cycle, since agriculture also undergoes definite stages from land preparation to harvesting (Table 1).

Table 1. Comparison of Bharatanatyam Margam with Agriculture

Margam Item	Symbolic Parallels with Agriculture
Alarippu - Awakening of the body and space	Tilling the soil, preparing for the dance ritual
Jatiswaram - Rhythm and movement	Similar to planting rhythms, early labor
Shabdam - Introduction of storytelling	Depicts emotions, invokes natural deities
Varnam - The centrepiece, deep emotional and symbolic content	Represents the growth period, nurturing with emotion and effort
Padam - Expressive interpretation	Harvesting feelings, reflections on nature and longing
Tillana - Joyous conclusion	Celebration of harvest or fullfillment
Mangalam - Closing prayer	Thanksgiving - much like Pongal prayers to Sun God

Representation Of Farming Activities Through Dance Movements

Though Bharatanatyam is a classical dance and have structured framework, it's liveliness and strength depends on how naturally it expression the everyday life. As described in the Natyashastra, the bodily expressions (Angika Abhinaya), is structured through Anga (major limbs), Pratyanga (intermediate limbs) and Upanga (the minor limbs including eyes and facial features). When all of the above work together, the human body forms a powerful tool to portray agricultural practices.

ISSN: 3049-2289

Depiction Of Agronomic Practices In Bharathanatyam

1. Land Preparation and Tillage

By using strong postures, bent torso positions and firm footwork integrated with the usage of Hastas like Ardhapathaka and Mushti (that represents a country plough) depicts the act of ploughing. The involvement of entire body by moving and bending forward represents the physical effort of farming and expresses the connection between farmer and land.

2. Seed treatment, sowing and nursery care

Gentle hand movements and controlled actions of arm (Anga) with walking actions of sowing seeds and use of hastas (symbols) like alapadma and katakamukha representing care in treating and sowing of seeds with facial expressions.

3. Transplanting, Fertilizer application and Crop Protection

Bending down and using hastas like mushti and Katakamukha visualises transplanting of seedlings. Sprinkling motions can suggest the application fertilizers.

4. Growth, Training, Pruning and Pollination

Stretching hands upwards with Tripathaka hastha represents growth of plants. Ardhapathaka hastha is used for representing cutting actions that depicts pruning and use of katakhamukha for depicting tying actions symbolises the action of Training. Blooming of flowers and the use of Bhramara hasta represents the bees that facilitates pollination.

5. Harvest and Celebrations

Dynamic use of angas in expansive movements represents reaping and collective celebrations. Expressive facial features enhance the portrayal of joy and fulfilment after successful harvest.

Usage Of Asamyukta And Samyukta Hastas To Depict Elements Of Agriculture

In Bharatanatyam, Hastas that is the hand gestures plays an very important role in visually representing nature and daily life. Th classical text Abhinaya Darpana explains the applications (viniyogas) of Asamyukta hastas (single hand gestures) and Samyukta Hastas (double hand gestures). Many of these Viniyogas directly depict the agricultural elements and farming activities.

Among the Asamyuktha hastas, Pataka hasta is predominantly used to represent natural elements. Its viniyogas include:

Vaarivahae (Rain clouds), Vane (Forest), Nadyam (River), Vayo (Wind), Khandanae (Cutting), Ghana tapae (Strong sunlight), Varsha dinae (Rainy day). These allow the dancer to portray the changing climatic conditions that influences agriculture. The act of sieving grains and removing the chaff can be depicted by using Pathaka hastha (Figure 1).

Figure 1. The act of sieving grains is depicted through the Pathaka Hasta

The Tripataka Hasta is used to depict Vriksha (trees), and Ketake Kusume, a type of flower. Similarly Ardhapataka Hasta represents Pallava (tender leaves), and tools like Krakacha (saw) and Churika (Knife), which may symbolically relate to agricultural practices like cutting and pruning.

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The Kartarimukha hasta viniyoga is used to depict the Creepers (Lathayamcha), representing the climbing plants of Cucurbitaceous family. Mayura hasta represents the Peacock that serves as symbol of indication of rain. Arala hasta signifies Prachanda Pavana, meaning a strong or violent wind, reflecting unfavourable weather conditions for crops.

The Mushti Hasta indicates Vasthuvadheenamcha Dharana, meaning the act of holding things, which symbolically represents holding of country plough, seeds, seedlings and farming tools (Figure 2 and 3). Kapitha Hasta is used for Godohanam, the act of milking cows, that directly connects with livestock activities in agrarian life. Katakamukha Hasta represents the act of plucking of flowers and it represents the action of transplanting seedlings (Figure 4).

Figure 2. Represents one hand mushti holding of produce and other hand ardhapathaka (Krakache) depicting the action of harvesting.

Figure 3. Represents one hand mushti holding of produce and other hand Thamrachuda representing a sickle depicting the action of harvesting

Figure 4. represents the action of transplanting paddy seeds with the one hand in katakhamuka hasta that reptresents placing of seedlings with other hand in mushti holding seedlings.

The Padmakosa Hasta relates with the natural produces like Bilwakapityadau (Wood apple), Fala (Fruits) and Kamala (Lotus), representing agricultural and botanical abundance. Sarpasirisha Hasta indicates Prokshana, the act of sprinkling water, which symbolically represents irrigation. Kangula Hasta depicts fruits and plantation tress like the Lakucha fruit and Kramuka (betel-nut) (Figure 5).

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Figure 5. Kangula hasta representing a fruit.

The Alapadma hasta represents elements like Tataka (pond or lake), Vikacha-abja (a fully bloomed lotus), Kappittha diphala (wood apple) and even Grama (village) thereby illustrating the environmental and social setting of rural life. Alapadma hastha can be used for depicting the action of broadcasting (Figure 6). Bhramara hasta is used to depict honey bee, symbolizing pollination essential for crop production (Figure 7). Hamsasya Hasta reprepresents Jala bindhu (water droplet) and Mallika (Jasmine flowers).

Figure 6. Illustration of the sowing action, conveyed through the Alapadma hasta.

The Sandamsha Hasta is used to depict Keetae (insects), an integral part of farming ecosystem. Mukula hasta denotes Bhojana (easting), and flowers suc as Kumuda (water lilly) and Kadali pushpa (Banana flowers). Trishula hasta represents the Bilwa flowers, a sacred and medicinal plant.

Among the Samyukta Hastas, Kartari Swastika Hasta is particularly relevant in representing the elements of nature. According to its viniyoga, it is used to depict tree branches (Shakha), mountain peaks (Adri Shikhara), and trees (Vriksha). Through this gesture, the dancer can visually express the broader landscape surrounding agricultural activity. Thus, through the symbolic use of these Hastas and their viniyogas, Bharatanatyam effectively portrays natural elements, plants, animals, and human activities associated with agriculture, demonstrating the deep connection between classical dance traditions and agrarian life.

Figure 7. Illustrates pollination, with one hand in Bhramara hasta depicting a honey bee and the other in Alapadma representing a flower.

Conclusion

Bharatanatyam reflects a deep connection between art, nature and everyday life. Through the use of various Hastas, body movements and expressions, the dance form can symbolically represent elements related to agriculture . The viniyogas of different Hastas described by the Abhinaya Darpana help dancers Portray natural elements and rural life. Similarly, the coordinated use of body parts explained by Natyashastra allows dancers to depict various agronomic practices. Thus, by interpreting farming activities through dance, it becomes possible to appreciate how classical art form preserves and communicate deep connection between human, nature and agricultural life.

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Harvesting of Mentha / Pudina

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Botanical Name:- *Mentha Spp.*

Family:- Labiatae

Chromosome Number:- 2n = 36, 48

Useful Part:- Leaves

Introduction

It is a perennial evergreen herbaceous plant. India produces about 75% of the world's Mentha. Besides India, it is cultivated in Brazil, Japan and China. In India, Uttar Pradesh is the Primary producer, accounting for 60% of the total area. It is also grown in Punjab, Haryana, Bihar and Madhya Pradeah.

Importance

It is mainly cultivated for its essential oils containing **Menthol**, **Menthon**, **Methyl Acetate** and **Linalool**. Fresh plants oil content between 0.12% to 0.45% volatile oil. The oil concentration is highest during the flowering stage. While oil is found in the stem, 85% of the total yield comes from the leaves.

Uses

Widely used in cosmetics and as a flavoring agent in foods like toffees and pan masala. Very effective in treating coughs, colds and back pain.

Harvesting

The amount of oil and menthol in mint increases with the age of the plants and after flowering, the amount of both oil and menthol starts decreasing. Its first harvest is done 80-90 days after sowing when 5 percent purple colored flowers appear and it is cut 10-12 cm above the ground surface. Its second harvest is done 60-70 days after the first harvest. In this way, two-three harvests are done in a year. While harvesting, it is kept in mind that the sky should be clear and there should be no possibility of rain. Harvesting is done only after the dew dries up. Irrigation is stopped 5-6 days before harvesting.

Distillation

The harvested crop is dried to one-third to one-fourth of its weight and put into a large vessel. Steam is passed through this vessel from the bottom. When this steam comes in contact with the plants, the oil present in the plants also turns into vapor. When this oily vapor passes through the condenser placed on top of the vessel, the steam condenses into water and the oil vapor turns into oil. This is collected in a vessel. Being lighter than water, the oil or menthol starts floating on the surface of the water. It is separated and cleaned and then filled in colored glass bottles and kept in low temperature rooms.

Yield

With advanced agronomic practices and favorable conditions, the average yield of mint is 300-400 quintals per hectare from 2-3 harvests, yielding 80-100 kg of oil.

Market Value

The market value of mentha (specifically Mentha Oil) in Uttar Pradesh currently ranges between ₹1,08,000 and ₹1,10,000 per quintal, depending on the exact mandi location. On the Multi Commodity Exchange (MCX), the futures/spot rate trades around ₹1000 to ₹1200 per kg.

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Linking Social Intelligence (SI) to the Life Tasks of Farmers

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Farming is not just about cultivating crops; it is also about managing relationships, communication, and community life. In today's changing agricultural landscape, farmers need more than technical skills, they require social intelligence to interact effectively with extension workers, participate in groups, negotiate in markets, and adapt to new challenges. Social intelligence helps farmers make better decisions, build strong networks, and improve both their livelihoods and community well-being.

1. Interacting with Extension Workers: Farmers need to communicate effectively with agricultural officers to gain knowledge about new techniques, schemes and inputs.
Example: A farmer listens carefully to an extension worker explaining drip irrigation and asks relevant questions to understand how it can benefit his dryland crops.

2. Participating in Farmer Producer Organizations (FPOs) or Self-Help Groups (SHGs): Being part of a group requires communication, empathy, and understanding group dynamics.
Example: A farmer attends regular SHG meetings, contributes to decision-making and helps resolve conflicts among members during loan sharing.

3. Conflict Resolution in Farming Communities: Disputes often arise over land, water use or shared equipment. Social Intelligence helps in managing emotions and resolving such issues constructively.
Example: Two farmers disagree over canal water timing; a third farmer mediates by helping them understand each other's needs and agrees on a shared schedule.

4. Market Negotiation and Selling: Farmers must interact with buyers and traders, negotiate prices, and understand market demand.

Example: A vegetable farmer at the mandi negotiates a better price by explaining the freshness and quality of his produce confidently and respectfully.

5. Family and Community Relations: Good relationships within the family and community are essential for emotional support, joint farming and crisis management.
Example: A farmer involves his wife and children in farming decisions, listens to their views, and maintains good ties with neighbours to share farm tools and labour.

6. Adapting to Change or Risk: Socially intelligent farmers accept advice, observe others and learn new ways to cope with changes like climate variation or market trends.
Example: After seeing a neighbour's success with organic farming, a farmer adopts similar practices, despite initial hesitation and risk.

7. Participating in Government Programs: Farmers must approach officials, fill forms and follow processes to avail benefits, this needs confidence and communication skills.
Example: A farmer applies for a solar pump subsidy scheme after consulting with the local agriculture department and helping others do the same.

8. Taking Part in Village Activities: Socially intelligent farmers take part in collective village development activities like watershed programs or Gram Sabha meetings. Example: A farmer speaks in a village meeting to support building a common storage shed for harvested crops.

Social intelligence plays a vital role in the everyday life of farmers, influencing how they communicate, collaborate, and adapt to change. From resolving conflicts to accessing government schemes and building strong community ties, these skills enhance both productivity and resilience. In a rapidly evolving agricultural environment, socially intelligent farmers are better equipped to succeed, ensuring sustainable growth for themselves and their communities.

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From mycelium to nanomaterials: Emerging trends in mushroom-based green nanotechnology

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The integration of mycology and nanotechnology has led to the emergence of mushroom-mediated green synthesis of nanoparticles as a sustainable alternative to conventional chemical methods. Mushrooms, rich in bioactive compounds such as polysaccharides, proteins, phenolics, and enzymes, act as natural reducing and stabilizing agents in the formation of nanoparticles. This eco-friendly approach minimizes toxic by-products, reduces energy consumption and enhances biocompatibility. The article highlights the ecological significance of fungi and mycelium, their role as natural bio factories and the mechanisms involved in nanoparticle synthesis, including reduction, nucleation, growth and stabilization. Various mushroom species have demonstrated the ability to produce metallic and metal oxide nanoparticles with promising antimicrobial, antioxidant and anticancer properties. These myco-nanoparticles find applications in medicine, agriculture, environmental remediation and biosensing. Despite challenges related to large-scale production, standardization and safety evaluation, mushroom-based nanotechnology represents a promising pathway toward sustainable innovation aligned with green chemistry and circular economy principles.

Introduction

The convergence of nanotechnology and biological sciences has opened new pathways for developing sustainable and environmentally friendly materials. In recent years, increasing concern over the ecological and health impacts of conventional chemical synthesis has driven a shift toward "green" approaches, where natural biological systems are used to fabricate nanomaterials. Among these, mushrooms have emerged as remarkably efficient biofactories due to their rich reservoir of bioactive compounds such as polysaccharides, proteins, phenolics, flavonoids and enzymes, which can act simultaneously as reducing and stabilising agents in nanoparticle formation. This unique biochemical composition enables mushrooms to convert metal ions into stable, functional nanoparticles through eco-friendly processes that require minimal energy and avoid toxic by-products. Mushroom-mediated green synthesis not only offers a cost-effective and scalable alternative to traditional methods but also produces nanoparticles with enhanced biocompatibility and diverse functional properties. As research continues to advance, the integration of mycology and nanotechnology is positioning mushrooms at the forefront of sustainable innovation, providing a promising route toward next-generation materials that align with global goals of green chemistry and circular economy.

Ecological and biotechnological importance of fungi and mycelium

Fungi are among the most mysterious and remarkable organisms on Earth. Fungi hidden beneath the soil lie an even more fascinating structure called mycelium, a vast underground network of thread-like filaments that acts as the living foundation of fungi. Mycelium is made up of microscopic branching filaments called hyphae, which spread through soil, wood and organic matter. This underground network acts as nature's recycler by decomposing dead plants, leaves and complex organic materials into simpler nutrients that enrich

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the soil. By breaking down organic matter and recycling nutrients, fungi play an essential role in maintaining ecological balance and supporting plant growth. Mycelium can transport water and nutrients across long distances and even form beneficial partnerships with plants through structures known as mycorrhizae. In these relationships, fungi help plants absorb nutrients such as phosphorus and nitrogen, while plants provide sugars produced through photosynthesis. Mushrooms are rich in bioactive compounds that offer antioxidant, antimicrobial, anticancer, anti-inflammatory and immune-boosting benefits. Beyond ecology, fungi are now driving innovations in biotechnology and nanotechnology. Researchers have discovered that mushrooms can act as natural "biofactories" for the green synthesis of nanoparticles. Mushroom extracts contain powerful reducing and stabilising compounds such as β-glucans, proteins, enzymes, flavonoids, terpenoids, and phenolic acids. These compounds can convert metal ions into nanoparticles without the need for toxic chemicals, making the process environmentally friendly and sustainable. Different mushroom species are capable of producing various nanoparticles with unique properties. Species such as *Pleurotus ostreatus*, *Ganoderma lucidum*, *Lentinula edodes* and *Agaricus bisporus* have been widely studied for synthesising silver, gold, zinc oxide, selenium, and copper nanoparticles. Scientists believe they may play a major role in future medicine, drug delivery systems, wound healing materials, environmental cleanup technologies and biosensors.

Green nanotechnology: A sustainable approach

Nanoparticles have unique properties with applications in various fields but conventional synthesis methods often involve toxic chemicals, costly equipment and high energy consumption. To overcome these limitations, scientists are increasingly turning toward green nanotechnology. Green nanotechnology focuses on producing nanoparticles using biological resources such as plants, algae, bacteria, fungi and mushrooms instead of hazardous synthetic chemicals. Among these biological systems, mushrooms and fungal mycelium have emerged as highly promising natural "nanofactories". Their rich composition of bioactive compounds acts as natural reducing and stabilising agents during nanoparticle formation. This biological process reduces environmental pollution and supports the principles of sustainable development and green chemistry. Mushroom-mediated nanoparticle synthesis is gaining attention because it combines efficiency with environmental safety. The process often occurs under mild environmental conditions without requiring harmful solvents or extreme temperatures. As a result, mushroom-based nanotechnology represents a cleaner and more sustainable alternative for the future. Mushrooms naturally possess the ability to absorb and degrade pollutants, and when combined with nanotechnology, their remediation potential becomes even more effective. Despite its enormous potential, green nanotechnology still faces challenges such as large-scale production, standardisation and commercial implementation. Further research is needed to improve nanoparticle stability, optimise synthesis methods and evaluate long-term environmental safety. As research continues to expand, fungal nanotechnology may become one of the most important green solutions.

Mechanism of fungal nano particle formation

Nanoparticles, typically ranging from 1 to 100 nm in size, can be synthesized through physical, chemical and biological methods. Among these, biological synthesis using plants, bacteria, fungi, algae and actinomycetes has gained significant attention due to its eco-friendly and sustainable nature, commonly referred to as green nanobiotechnology or myco-synthesis in the case of fungi. Green nanotechnology is based on principles such as minimizing waste generation, reducing the use of toxic chemicals, employing renewable biological resources, improving energy efficiency, utilizing safer solvents and developing biodegradable and recyclable

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materials. Fungi, particularly mushrooms, have emerged as efficient bio factories for nanoparticle synthesis because of their rich diversity of bioactive metabolites and extracellular enzymes. Several fungal genera, including *Aspergillus*, *Fusarium*, *Verticillium*, *Trichoderma*, *Rhizopus*, *Penicillium* and edible mushrooms such as *Pleurotus* spp., have been successfully employed for the biosynthesis of metallic and metal oxide nanoparticles including silver (Ag), gold (Au), zinc oxide (ZnO), titanium dioxide (TiO_2), magnesium oxide (MgO), copper (Cu), and cadmium sulfide (CdS) nanoparticles (Adebayo *et al.,* 2021).

The mechanism of fungal nanoparticle synthesis involves a series of interconnected stages including reduction, nucleation, growth and stabilization. Initially, metal ions such as Ag^{+}, Au^{3+}, or Cu^{2+} are reduced into their zero-valent metallic forms (Ag^{0}, Au^{0}) through electron donation by mushroom-derived biomolecules. These biomolecules include polysaccharides (β-glucans and chitin), proteins, peptides, phenolics, flavonoids, terpenoids, vitamins, alkaloids, tannins, saponins, amino acids, and other secondary metabolites, which function as natural reducing and capping agents. Enzymes such as reductases, particularly nitrate reductase, play a crucial role in facilitating intracellular or extracellular reduction of metal ions. Following reduction, the metal atoms aggregate to form small nuclei that act as seeds for nanoparticle formation, a process known as nucleation, which largely determines nanoparticle size and morphology. During the growth phase, additional reduced atoms accumulate onto these nuclei, resulting in the formation of stable nanoparticles, generally ranging between 10 and 100 nm depending on reaction conditions. Finally, stabilization or capping occurs when proteins, polysaccharides, and other biomolecules bind to the nanoparticle surface, preventing aggregation through steric and electrostatic interactions and thereby enhancing nanoparticle stability, biocompatibility and functionality. The efficiency and characteristics of myco-synthesized nanoparticles are strongly influenced by factors such as temperature, pH, fungal biomass concentration, and medium composition. Overall, fungal nanoparticle synthesis represents a simple, cost-effective, and environmentally benign approach for producing functional nanomaterials with promising applications in biomedical, agricultural, environmental, and industrial sectors (Malakar *et al.,* 2025). Schematic representation of mushroom-mediated green synthesis of nanoparticles illustrating the major stages involved, including selection of functional mushroom species, extraction of bioactive compounds, optimization of reaction conditions, biotransformation of metal ions into nanoparticles, physicochemical characterization, and evaluation of their biomedical, agricultural, antioxidant, antimicrobial, and environmental applications represented in Figure 1.

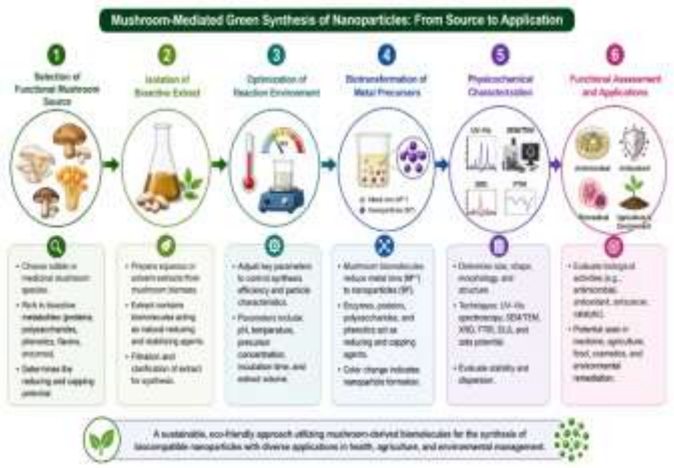

Figure 1: Overview of mushroom-mediated green synthesis of nanoparticles and their characterization and applications

Myco nanoparticles and their applications

Antimicrobial resistance (AMR) has emerged as a major global challenge due to the excessive and improper use of antibiotics, leading to the development of drug-resistant pathogens. In agriculture, AMR threatens crop productivity and food security by reducing the effectiveness of conventional chemical treatments against plant diseases. As a sustainable alternative, mushrooms have gained attention for their ability to synthesize eco-friendly nanoparticles with strong antimicrobial properties. Mushrooms contain diverse bioactive compounds such as β-glucans, phenolics, flavonoids, proteins, terpenoids, and enzymes that act as natural reducing and stabilizing agents in the green synthesis of nanoparticles, known as myco-nanoparticles. Edible and medicinal mushrooms including *Ganoderma lucidum*, *Pleurotus ostreatus, Lentinula edodes* and *Agaricus bisporus* are widely used for producing silver, copper oxide, and zinc oxide nanoparticles through environmentally friendly methods without toxic chemicals. Mushroom-derived nanoparticles exhibit antimicrobial activity through several interconnected mechanisms. One of the primary mechanisms involves the disruption of microbial cell membranes. Silver, copper oxide, and zinc oxide nanoparticles synthesized from mushrooms attach to bacterial surfaces and increase membrane permeability, causing leakage of cellular contents and eventual cell death. Their nanoscale size enables them to penetrate microbial membranes more effectively than many conventional antibiotics. Another major antimicrobial mechanism is the production of reactive oxygen species (ROS). These highly reactive molecules create oxidative stress within microbial cells by damaging proteins, lipids, enzymes, and DNA. Excess ROS generation disrupts cellular metabolism, inhibits energy production, and ultimately leads to microbial destruction. This oxidative damage is especially effective against antibiotic-resistant pathogens. Mushroom-derived nanoparticles also possess significant antibiofilm activity. Biofilms are protective microbial communities that shield pathogens from antibiotics and immune responses. Myco-nanoparticles penetrate the extracellular polymeric matrix of biofilms and interfere with quorum sensing pathways that regulate microbial communication (Grace *et al.,* 2025). By disrupting biofilm formation, these nanoparticles enhance the susceptibility of pathogens to antimicrobial treatment. In addition, mushroom nanoparticles improve plant and soil health through their biodegradable and biocompatible nature, minimizing environmental pollution compared with conventional agrochemicals. Their synergistic interaction with existing antimicrobial agents may further improve disease management and reduce resistance development. Although challenges remain in standardization and large-scale production, mushroom-mediated nanotechnology offers a promising green approach for sustainable agriculture and antimicrobial resistance management. With continued research, myco-nanoparticles could become valuable tools for eco-friendly plant disease control and improved agricultural productivity. Different mushroom species, their bioactive compounds, synthesized nanoparticles, and potential biomedical, agricultural, and environmental applications has been represented in table 1.

Mushroom species	Nanoparticles	Bioactives	Role	Size/Features	Applications
Pleurotus ostreatus	AgNPs, Carbon nanodots	β-glucans, proteins, phenolics	Reduction + capping	10–70 nm	Antimicrobial, wastewater treatment
Pleurotus eryngii	Chitosan NPs	Chitin, polysaccharides	Structural polymer	Biopolymer	Drug delivery
Pleurotus citrinopileatus	CuO NPs	Phenolics, flavonoids	Reduction	20–100 nm	Antibacterial

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Pleurotus spp.	Carbon nanodots	Proteins, carbohydrates	Carbonization	Fluorescent	Bioimaging
Lentinula edodes	Chitin NC, ZnO NPs	β-glucan, phenolics	Reduction	35–200 nm	Drug delivery
Ganoderma lucidum	AgNPs, AuNPs	Terpenoids, polysaccharides	Electron donation	2–70 nm	Anticancer
Agaricus bisporus	AgNPs, AuNPs	Proteins, amino acids	Reduction	10–50 nm	Antibacterial
Phellinus linteus	AgNPs	β-glucans	Stabilization	10–70 nm	Antioxidant
Schizophyllum commune	Nanofibers	β-glucan	Polymer templating	Nanofiber	Drug carrier
Fomes fomentarius	AgNPs	Flavonoids	Reduction	10–20 nm	Antimicrobial
Lactarius piperatus	AgNPs	Phenolics	Reducing agent	33–64 nm	Catalysis
Volvariella volvacea	AgNPs, AuNPs	Proteins	Capping	2–70 nm	Nanomedicine
Cordyceps militaris	Metal NPs	Polysaccharides	Reduction	Variable	Immunomodulation
Cantharellus cibarius	Au, Ag NPs	Phenolics, vitamins	Reduction	Variable	Imaging

Table 1: Different mushroom species, their bioactive compounds, synthesized nanoparticles, and potential biomedical, agricultural, and environmental applications

Challenges and safety considerations, prospects: the road ahead for green nanotechnology

Green nanotechnology, particularly the synthesis of nanoparticles using mushrooms and fungi, has emerged as a promising alternative to conventional chemical methods. Despite the advantages, several scientific, safety and regulatory challenges must still be addressed before mushroom-derived nanoparticles can be widely commercialized and used in clinical applications. One of the major concerns surrounding nanomaterials is safety. Although myco-nanoparticles are generally considered more biocompatible than chemically synthesized nanoparticles, their effects on living systems depend on factors such as particle size, shape, surface charge, concentration, mushroom species used and route of exposure. At uncontrolled or excessive doses, nanoparticles may accumulate in tissues and cause oxidative stress, membrane damage or disruption of cellular functions (Törös *et al.,* 2025). However, many studies have demonstrated that biosynthesized nanoparticles such as silver, zinc oxide and copper oxide nanoparticles exhibit relatively low toxicity when used at controlled concentrations. Even with these encouraging findings, the long-term effects of myco-nanoparticles are still not fully understood. Another important challenge lies in the reproducibility of fungal nanoparticle synthesis. Biological systems are naturally variable, and different fungal strains, environmental conditions, nutrient availability, pH, temperature and incubation time can significantly influence the size, shape and stability of the nanoparticles produced. Variations in cultivation conditions may lead to inconsistencies in the final product, making large-scale industrial production difficult. Maintaining sterile conditions is equally critical, as fungal cultures are highly vulnerable to contamination from bacteria and other microorganisms. To overcome these limitations, researchers are focusing on standardizing culture conditions, optimizing growth parameters, and selecting easily cultivable fungal strains tailored for specific nanoparticle applications. Controlled preparation methods such as filtration, centrifugation, enzyme isolation, and standardized extraction procedures are being developed to improve consistency and reliability. Safety assessment and regulation are equally important for the future of green nanotechnology. Future development of myco-nanoparticles is expected to follow a "safety-by-design" strategy, where potential environmental and health risks are considered during the earliest stages of nanoparticle development. This approach aims to design safer nanomaterials while minimizing harmful side effects and environmental impacts. As scientific understanding improves, green nanotechnology has the potential to revolutionize sustainable medicine, agriculture, environmental remediation, and advanced materials development. By combining biological innovation with responsible safety practices and standardised production methods, mushroom-derived nanoparticles may become an important component of future eco-friendly technologies.

Conclusion

Mushroom-mediated green nanotechnology represents a transformative and eco-friendly approach to nanoparticle synthesis, offering significant advantages over conventional chemical methods. The unique biochemical composition of mushrooms enables efficient, low-cost, and sustainable production of nanoparticles with diverse functional properties. These myco-nanoparticles show immense potential in addressing global challenges such as antimicrobial resistance, environmental pollution, and the need for sustainable agricultural practices. However, challenges including reproducibility, large-scale production, and comprehensive safety assessment must be addressed to enable wider commercialization and application. Future research focusing on process optimization, standardization, and "safety-by-design" strategies will be crucial in unlocking the full potential of fungal nanotechnology. Overall, the convergence of mycology and nanoscience paves the way for innovative, environmentally responsible technologies that can contribute significantly to sustainable development.

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Soil Health and Soil Productivity Improve by Enhancing Rhizosphere Biota

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Soil fertility, climate change, environmental deterioration, urbanization, and the growing demand for food due to the growing global population are just a few of the many issues facing agriculture in the twenty-first century. Increasing crop output with the current land base is one of the major difficulties facing the scientific community in the interim. In this sense, the sporadic and careless use of agrochemicals, such as pesticides and synthetic fertilizers, has increased agricultural yields per acre in traditional farming, but at a significant environmental cost. The development of pesticide resistance in agricultural pests is another significant issue in contemporary agriculture. Therefore, using alternative techniques that can increase agricultural yields in an environmentally responsible way is necessary for the future of sustainable crop production. The use of rhizobacteria—more especially, plant growth-promoting rhizobacteria (PGPR)—as a substitute for conventional pesticides has drawn a lot of interest from scientists. Through a variety of processes, these rhizobacteria reduce plant pests, encourage plant development, and create resistance to a range of abiotic stressors. The bioremediation of contaminated soils, biocontrol of pests, and promotion of plant development are all examined in detail in this study. The effects of PGPR inoculation on plant development and stress tolerance are also highlighted. Along with potential future paths for their sustainable usage, the benefits and drawbacks of using rhizobacteria in agriculture are also extensively examined.

1.Introduction

Crop production is increasingly threatened by various biotic and abiotic stresses, while the growing global population demands higher agricultural productivity from limited arable land. Conventional agricultural practices, including excessive use of fertilizers, pesticides, and untreated wastewater, have contributed to environmental pollution and soil degradation. Furthermore, rapid urbanization and industrialization continue to reduce agricultural land, emphasizing the need for sustainable approaches to improve crop productivity without harming natural resources. Among the promising strategies, the use of plant growth-promoting rhizobacteria (PGPR) has gained significant attention. These beneficial rhizosphere microbes enhance plant growth through multiple direct and indirect mechanisms, including improved nutrient availability, phytohormone regulation, root colonization, and stress tolerance. PGPR also contribute to biocontrol and bioremediation by producing antibiotics, siderophores, biosurfactants, and other beneficial compounds.

2. PGPR-Mediated Mechanisms for Sustainable Plant Growth

2.1. Nitrogen Fixation by Rhizoshpere biota,

It is essential for plant growth and other metabolic functions, making it one of the most important elements. Plants are unable to absorb nitrogen (N2), which accounts for 78% of all gases in the environment. The process by which certain bacteria and archaea transform nitrogen into ammonia (NH3) through a nitrogenase protein complex is known as biological nitrogen fixation (BNF). There are many nitrogen fixers in nature, and microorganisms' ability to fix nitrogen can replace synthetic fertilizers. There are two types of nitrogen-fixing microbes: non-symbiotic (free-living and endophytic organisms) and symbiotic (mutualistic interaction between bacteria and leguminous plants and non-leguminous trees) [Ali *et.al.* 2017]. Frankia and Rhizobium species are well-known symbiotic N2 fixers in soil, while diazotrophic PGPR, such as Cyanobacteria, Azospirillum, Pseudomonas, Azotobacter, Acetobacter, and Nostoc, are non-symbiotic nitrogen-fixing microbes [Bhattacharyya *et. al.* 2012]. In the natural world, non-symbiotic bacteria are crucial because they fix less nitrogen yet still supply enough to meet the needs of host plants. Root nodules are the consequence of a complicated process of infection and establishment between symbionts and the roots of leguminous plants. The process of nitrogen fixation requires energy in the form of ATP (adenosine triphosphate), which is stored in the form of glycogen after bacterial carbon resources undergo oxidative phosphorylation. Nif (nitrogenase complex) genes are responsible for fixing nitrogen in both symbionts and free-living non-symbionts [Glick 1995].

The nif genes encode the enzymes that fix atmospheric N2 into a form of nitrogen that plants can use. Nitrogenase complex is the main enzyme that nif genes encode. Nif genes encode both enzymes and regulatory proteins for N2 fixing. The induction of nif gene expression is caused by the host plant's root environment's low nitrogen content and high oxygen (O2) concentration. Although oxygen is necessary for Rhizobium and bacteroid organisms to breathe, it also inhibits the activity of the nitrogenase enzyme and is a negative regulator of nif genes. In root nodules, bacterial hemoglobin, which binds free oxygen radicals, keeps O2 from impeding N2 fixation while simultaneously supplying enough O2 for bacteroid respiration [Bhattacharyya *et. al.* 2012].

2.2 Phosphorus Mobilization

Phosphorus (P), the second most significant macro element after nitrogen, is necessary for adequate plant feeding. Numerous metabolic processes in plants, such as photosynthesis and energy transport, depend on it. Although P is present in excess in most soils, only 0.1% of the total phosphorus in the soil is available for plant utilization [Alori *et. al.* 2017]. Phosphorus becomes immobilized in soil due to complex interactions with various cations, such as Ca2+ and Mg2+ in alkali soils and Fe3+ and Al+ in acidic soils. In most soils where available P is insufficient for plants, commercial fertilizers are used to meet plant needs. An estimated 52.3 billion tons of phosphorus fertilizers are used annually on agricultural land. Overuse of synthetic fertilizers causes eutrophication of water bodies as well as environmental risks, such as global warming from nitrogen oxide generation. On the other hand, microorganisms that promote plant growth provide a viable way to increase crop yield without harming the environment. By facilitating the mineralization of organic P in soil, these microorganisms raise the availability of phosphorus in soil. P solubilization is necessary for microorganisms to mineralize organic P, and soil pH has a significant impact on this process. By creating different organic and inorganic acids as well as other metabolites, these microorganisms alter the pH of the soil through a process called rhizosphere acidification. Phosphate-solubilizing bacteria (PSB) include several Rhizobium, Pseudomonas, and Bacillus species [Umar *et. al.* 2020].

3. **Biosynthesis of Plant Hormones**

Phytohormones or plant growth regulators are organic constituents that promote plant growth. PGPR stimulate the production of phytohormones in plants and hence promote their growth and development. Various bacteria performing this role have been isolated and characterized, and promising results in crop growth promotion have been reported. Phytohormones such as gibberellins, cytokinin, abscisic acid, ethylene, and auxin can promote the blooming of root cells via the overproduction of adjacent roots, with a subsequent increase in nutrient and water uptake. The system that plants use to endure stress is complex and intricate. Microorganisms use different biochemical and molecular mechanisms to improve plant growth. PGPR improve plant growth by adjusting hormones and the accessibility of nutrients in plants and stimulating resistance to disease-causing organisms. These also generate specific metabolites that control plant pathogens in the root zone. For example, rhizobitoxine increases plant growth and expansion in stressed conditions by limiting ethylene production. In addition, different bacteria have sigma factors that modify the expression of plant genes in a way that increases their survival in stress situations [Gupta *et. al.* 2014].

The most commonly studied phytohormone produced by PGPR is indole-3-acetic acid (IAA), which facilitates plant–microbe association. The role of IAA depends on the endogenous IAA levels in plants. Auxins produced by PGPR are involved in plant growth promotion by stimulating transcriptional alterations in hormones, enhancing root biomass, shrinking stomata size and density and triggering the expression of auxin response genes. Cytokinins and gibberellins are also produced by various PGPR. Several strains of PGPR can stimulate a comparatively huge volume of gibberellins, leading to increased plant shoot growth. The association of these hormones with auxins can modify the root structure. GPR also produce cytokinins, which increase the production of root exudates by the plant, perhaps increasing the presence of PGPR that are associated with the plant. The role of PGPR in stressed and unstressed environments has been studied and they frequently appear to provide better growth stimulation in stressful situations, such as drought stress. stimulates the expression pathogenesis-related genes, facilitated via phytohormone signaling pathways and defense regulatory proteins, to protect plants against future pathogen attacks [Pieterse *et. al.* 2014].

4. Root Colonization for Better Plant Nutrient Acquisition

Plant roots interact with a wide range of soil microorganisms inhabiting the rhizo sphere. An important aspect of such associations between the plant roots, rhizo sphere, and rhizobacteria is the improvement in root growth and proliferation, which play significant roles in the transfer of nutrients and water to the upper plant parts. For instance, such an association results in enhanced root exudation which, in turn, attracts microbial candidates toward the vicinity of the root, which eventually results in aggressive root colonization. The concept of root colonization denotes the multiplication of bacterial populations ec tophytically in the rhizosphere and endophytically inside the roots. Root colonization by PGPRis considered essential for plant development. In the process of root colonization, rhizobacteria propagate from the source of the inoculum, such as in seed treatments, to the actively growing root region and proliferate in the rhizosphere [Ramaekers *et. al.* 2010].

5. PGPR's Mode of Action as Biocontrol Agents

5.1. Synthesis of Antibiotics

The key method of plant growth-promoting bacteria for combating phytopathogen caused damage is the production of antibiotics. The biocontrol abilities of Pseudomonas strains are largely dependent on aggressive root colonization, induction of plant systemic resistance, and the development of antifungal antibiotics. The potential of rhizobacteria as biocontrol candidates against phytopathogens is generally associated with the development of one or more antibiotics. Over the last two decades, the concept of antibiosis, or biocontrol based on the synthesis of molecules that destroy or slow the growth of the target pathogen, has become well defined. Antibiotics are a diverse group of organic, low-molecular-weight compounds that inhibit the growth or metabolic activities of bacteria and other microorganisms. Antibiotics produced by

Pseudomonads include 2,4-diacetylphloroglucinol (DAPG), amphisin, hydrogen cyanide, phenazine, oomycin A, tropolone, pyoluteorin, tensin, pyrrolnitrin, and cyclic lipopeptides, while Streptomyces, Bacillus, and Stenotrophomonas spp. produce kanosamine, oligomycin A, xanthobaccin, and zwittermicin, which have been identified as antibiotics that have antibac terial, antifungal, antiviral, anthelminthic, antimicrobial, cytotoxic, phytotoxic, antioxidant, and antitumor properties [Abbas *et. al.* 2018].

5.2. Rhizosphere Competence and Root Colonization

It is well recognized that for bacteria to be considered valid PGPR, a biocontrol agent must colonize the rhizosphere and the surface of the plant. Therefore, if a PGPR species does not colonize the roots, it is useless as a biocontrol agent against root disease. Pseudomonas and Bacillus species are the most common PGPRs that invade roots in a range of crops. Many members of this group may successfully colonize the rhizosphere, are widely distributed in soil, and produce a variety of chemicals that protect against a wide range of plant diseases [Rangarajan *et. al.* 2003].

5.3. Root Colonization, Increased Nutrient Acquisition, and Antagonistic Activity against Pathogens

Antagonists are bacteria that exhibit antagonistic activity against a pathogen, whereas biocontrol agents are bacteria that reduce the incidence or severity of plant diseases. The production of hydrolytic enzymes that can lyse pathogenic fungal cells, such as chitinases, glucanases, proteases, and lipases, competition for nutrients and proper colonization of niches at the root surface, control of plant ethylene levels through the ACC deaminase enzyme, which can act to modulate ethylene levels in a plant in response to infection-induced stress, and development of siderophores and antibiotics. The development of secondary metabolites, such as auxins, IAA, cytokinins, riboflavin, and vitamins, may be adirect result of the PGPR stimulation of plant growth [Campanoni *et. al.* 2003].

5.4. Mechanisms of Cell Wall-Degrading Enzyme Production

The production of enzymes that degrade cell walls is one of the main ways biocontrol agents treat soilborne diseases. Biocontrol strains of PGPR release enzymes that break down cell walls, such as β-1,3-glucanase, chitinase, cellulase, and protease, which considerably impede the hyphal growth of fungal infections. β-1,3-glucanase, which is produced by Streptomyces and Paenibacillus species, breaks down the fungal cell walls of pathogenic F. oxysporum. A vital part of fungal cell walls, chitin is a soluble linear polymer of β-,4-N-acetylglucosamine that is broken down by the enzymes chitinase and β-1,3-glucanase. Bacillus cepacia produces B-1,3-glucanase, which breaks down the cell walls of soilborne pathogens such as S. rolfsii, P. ultimum, and R. solani. Potential biocontrol agents with chitinolytic activity include B. licheniformis, B. cereus, B. circulans, and B. thuringiensis. Among Gram-negative bacteria, chitinolytic activity have been reported in Serratia marcescens, Enterobacter agglomerans, Pseudomonas aeruginosa, and Pseudomonas fluorescens [Budi *et. al.* 2000].

6. Modes of Action of PGPR in Bioremediation

6.1. Siderophores and Heavy Metal Removal

Siderophores are produced by microorganisms and have a high affinity for chelating iron. Different plant growth-promoting rhizobacteria (PGPR) create siderophores. Siderophores affect how soluble iron phosphate is in soil. Bacterial activities that improve mineral nutrient absorption by plants can aid plant growth in trace metal-contaminated soils because they produce siderophores, which are low-molecular-weight proteins. In iron-limiting conditions, secondary metabolites that chelate iron are found in fungi, bacteria, and plants. Siderophore-producing

PGPR can either directly increase plant iron nutrition to promote plant development or indirectly decrease plant pathogen activity in the soil root zone by limiting their iron availability. Iron is more frequently found as Fe3+, which is bonded to insoluble hydroxides and oxyhydroxides, preventing microbes and plants from accessing it. In comparison to Fe2+ or other trace metals, such as Co, Cu, Cd, Pb, Ni, Cr, and Zn, Fe3+ has a higher affinity for siderophores. The iron supply to developing plants under trace metal stress becomes increasingly important since rhizobacterial siderophores tend to lessen the stress caused by trace metal pollution [Gamalero and Glick 2011].

6.2. Biosurfactant-Mediated Heavy Metal Remediation

Biosurfactants classified as amphiphilic compounds, which possess significant hydrophobic and hydrophilic groups, are among the most important agents in the remediation of contaminants in the rhizosphere. Surfactants include a hydrophilic component (functional groups) that makes them soluble in water and a hydrophobic component that enables them to form hydrophobic interiors, interact with hydrophobic compounds, and adsorb at interfaces (like air/water) to reduce surface tension. Biosurfactants, the biobased substitutes for surfactants, have gained appeal as a result of strong hazardous manifestations. Microbial surface-active metabolites known as biosurfactants are metal-complexing agents that have been demonstrated to be helpful in the cleanup of areas contaminated with heavy metals. Biosurfactants may be able to replace traditional remediation techniques due to their special qualities. These are more biodegradable and environmentally friendly, and they are less harmful. Other advantages include their capacity to be produced from inexpensive organic wastes and agro-based raw materials, as well as their capacity to continue operating in the rhizosphere under conditions of severe pH, temperature, and salt concentration [Lima *et. al.* 2011].

7. Conclusion

Because they enhance root colonization, boost nutrient availability, generate plant growth hormones, and protect plants from infections, plant growth-promoting rhizobacteria (PGPR) are essential to sustainable agriculture. They promote plant growth by the production of antibiotics, phosphate mobilization, nitrogen fixation, induced systemic resistance, and cell wall-breaking enzymes. Additionally, PGPR helps with bioremediation by producing siderophores and biosurfactants that help remove heavy metals from contaminated soils. Thus, PGPR are effective and eco-friendly techniques for increasing agricultural productivity, managing illness, and preserving environmental sustainability.

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ISSN: 3049-2289

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Relevance of the golden ratio and Fibonacci sequence in Today's World – The unseen gift within nature

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Mathematical terms such as the Golden Ratio and the Fibonacci Sequence appear repeatedly in nature and have a significant relevance in Agriculture and modern-day applications. The Golden ratio is always associated with balance, symmetry and a pleasing aesthetic appearance whereas the Fibonacci series is a numerical pattern in which each number is the sum of its preceding numbers. In agriculture, these principles can be seen in natural plant structures noticed in the vertical growth of the stems, flowers, leaflets and so on where they contribute to efficient light and space optimization and photosynthesis up to a certain extent.

Introduction

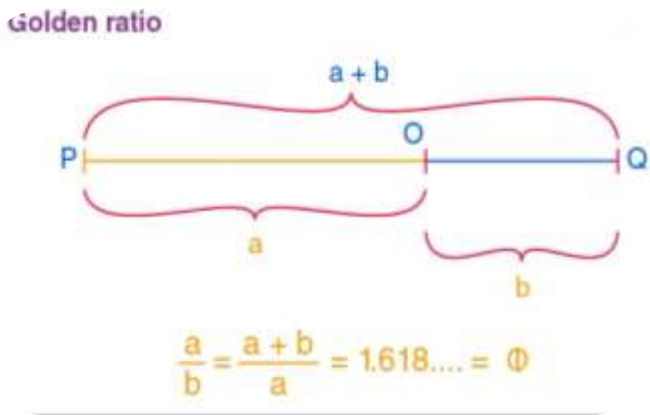
Mathematical concepts such as the Golden Ratio and the Fibonacci sequence were initially discovered in Greece around 300 BCE. At first glance, one might wonder what such terms have to do with reference to nature. What is the importance or prevalence of such things in today's world? This article explains each of the terms and their importance in contemporary Agriculture and how these concepts act as a bridge connecting Mathematics with nature and its occurrence as a recurrent theme.

What is the famous golden ratio?

The golden ratio has been studied for centuries by numerous statisticians and scientists but was first officially defined by Greek Mathematician, Euclid. It is represented by the Greek alphabet phi(Φ) and is equal to a value of approximately 1.618. This ratio present on any object is said to be aesthetically pleasing to the viewer. Two quantities are in the golden ratio if their ratio is the same as the ratio of their sum to the larger quantity. For a layman's understanding it can be explained like this:

When a line is divided into two parts, the long part divided by the short part is equal to the total length divided by the long part.

For example, if two quantities a and b are present, where a is greater than b, then:



What is the Fibonacci Sequence and its relationship to the golden ratio?

The Fibonacci Sequence was founded by Italian Mathematician, Leonardo Fibonacci and revolutionized the field of Mathematics. This sequence is nothing but a series of numbers where every successive number is the sum of the two previous numbers. The Fibonacci Sequence is as follows:

0,1,1,2,3,5,8,13,21,34... and so on.

As explained above, the first two terms are '0' and '1' whose sum is '1' which becomes the third term. Consecutively, the fourth term is '2' formed by the sum of the previous two terms. Thus, the sequence

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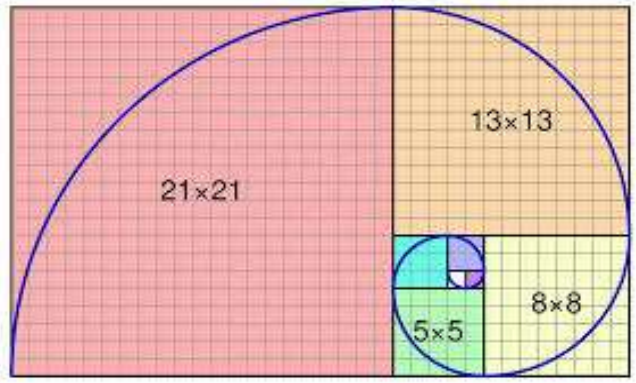
continues up to infinity in the very same manner. From the Fibonacci series the Fibonacci spiral can also be derived, which is a logarithmic spiral which that connects the corners of the squares, whose sides are of the lengths of the numbers in the Fibonacci sequence.



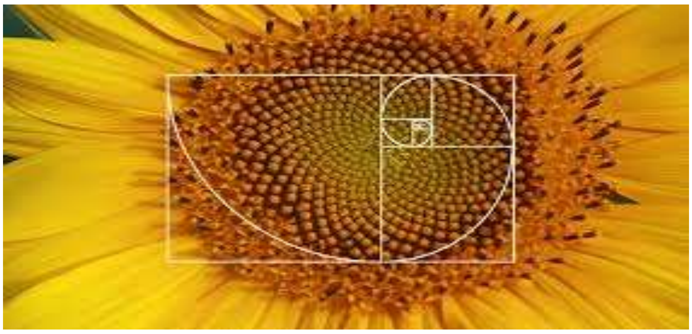
F(n)	F(n-1)	F(n)/F(n-1)
1	1	1
2	1	2
3	2	1.5
5	3	1.666666667
8	5	1.6
13	8	1.625
21	13	1.615384615
34	21	1.619047619
55	34	1.617647059
89	55	1.618181818

Now let's get into the heart of the matter, what is the true relationship between the Fibonacci sequence and the golden ratio, how is it all connected? In this interesting case, you may notice that the ratio of the successive numbers in the Fibonacci series comes closer to the Golden ratio (1.618) as the sequence progresses to infinity.

Relevance of the golden ratio and Fibonacci sequence in Agriculture:

The principles of the Fibonacci numbers and the Golden ratio appear in many patterns and structures throughout nature as the golden ratio tends to give a symmetrically pleasing, artistic effect to the viewers creating a sense of balance and harmony in nature.

For example, in the sunflower, the construction of each of the individual florets forms a spiral pattern. If we count each spiral, the Fibonacci number series is consistently found, and the seeds are packed in an efficient manner. Taking inspiration from the sunflower's floret arrangement, scientists experimented with creating a new type of solar concentrator array where solar panels are arranged in spirals to maximize sunlight absorption, reduce the shading effect and minimize 20% of the land used compared to the previous attempts made.



Let's take a look at another example, the unfolding of a fern frond. Young growing fern fronds unfurl in perfect Fibonacci spirals thus maximizing space efficiency. Similarly, the designing of greenhouses and their layouts by architects is a form of biomimicry to maintain optimum light concentration and space.

Another method is to make use of spiral planting, to grow crop circles and is once again a form of the Fibonacci sequence leading to effective land utilization and light exposure, along with enhanced irrigation for increased crop productivity. Spiral planting can also be done in a much smaller scale like growing small spiral herb gardens in one's own backyard. Along with the above listed advantages, it allows for ease of harvest and is a form of permaculture (a form of agriculture that follows a

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self-sustaining natural ecosystem) as well. By following such natural patterns, we can cultivate viable agricultural practices.

Phyllotaxis in Plants: Phyllotaxis refers to the arrangement of leaves on a plant. Leaves on all plants grow in such a manner such that the upper leaves do not shade the lower leaves thus increasing the surface area for photosynthesis, boosting growth and allowing trees to form a dense canopy easily without compromising on photosynthetic efficiency. Phyllotaxis is also what helps scientists breed and develop high yielding crops.

The Golden Angle: The golden angle which is equal to 137.5^{o} is found in the whorl and petal arrangement of flowers, like daisies, roses and succulents. It is referred to as the "golden angle" because no two petals will coincide or intersect with each other at this point. Many other examples that can be observed include the bracts of pinecones, scales of pineapples, the rings of a seashell, etc. The advantage of the golden angle is the packing efficiency, meaning it allows the maximum number of items to fit in a tight space.

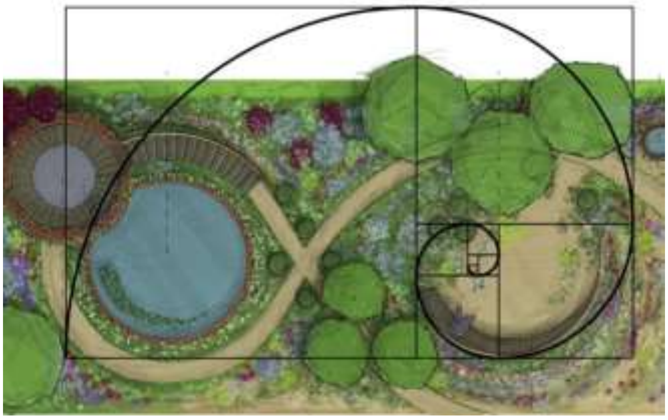
The golden ratio in marketing:

The golden ratio is present in everything all around us. It is human nature to be attracted to those plants which are more beautiful and aesthetic in nature. The crux of the matter is this: The closer an entity of nature (such as flowers, fruits, plants, etc.,) is to the golden ratio, the more alluring and enchanting it appears to the viewer. Now let's apply this concept to the real world, customers always buy flowers that have the perfect petal arrangement because of the inherent nature of the golden ratio present within it. This is exactly why Floral Designers or Event Florists use flowers like Roses, Daisies, Lilies, Gerberas, Buttercups, Chicory and so on for floral arrangements, not just because of the variety of colors available for each flower but also for the overall captivating effect the compact arrangement of the petals has on the public eye.

What about its application in commercial landscaping? Planning the design of a garden or the placement of bushes or trees, flowering plants, outlining the non-flowering components such as statues, benches, fountains, and so on are done by landscape architects who may draw plans keeping the Golden ratio and Fibonacci series in mind to provide a sense of coherence and radial symmetry while also making use of every square feet of soil to the maximum extent. For example, the "inspiration garden *Fibonacci*" at Bloemenpark Appeltern in the Netherlands is a modern streamlined garden without any straight lines and with flowers in different color combinations throughout the spiral.

Conclusion:

In conclusion, both of these concepts are divine proportions found innately within nature and the use of these principles in the real world leads to feasible solutions and models with higher efficiency and optimization, which in turn is beneficial to mankind in today's economy. Overall, the Golden ratio and Fibonacci sequence demonstrate the deep connection between mathematics and nature, offering practical and sustainable solutions that improve agricultural productivity, optimization, and aesthetic value in the modern world.



Ex: Garden design with the Fibonacci series and Inspiration Garden 'Fibonacci', Netherlands

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Genome editing for improving stress tolerance, nutritional quality and post-harvest shelf life of Vegetable Crops

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Agricultural production relies on horticultural crops, including vegetables, fruits, and ornamental plants, which sustain human life. With an alarming increase in human population and the consequential need for more food, it has become necessary for increased production to maintain food security. Conventional breeding has subsidized the development of improved verities but to enhance crop production, new breeding techniques need to be acquired. CRISPR-Cas9 system is a unique and powerful genome manipulation tool that can change the DNA in a precise way. Based on the bacterial adaptive immune system, this technique uses an endonuclease that creates double-stranded breaks (DSBs) at the target loci under the guidance of a single guide RNA. These DSBs can be repaired by a cellular repair mechanism that installs small insertion and deletion (indels) at the cut sites. When equated to alternate editing tools like ZFN, TALENs, and meganucleases, CRISPR- The cas-based editing tool has quickly gained fast forward for its simplicity, ease to use, and low off-target effect. The CRISPR-based tool is the most appropriate one with the prospective goal of generating non-transgenic yields and avoiding the regulatory hurdles to release the modified crops into the market. Although several challenges for editing horticultural, industrial, and ornamental crops remain, this new novel nuclease, with its crop-specific application, makes it a dynamic tool for crop improvement.

Introduction

Chronic malnutrition continues to affect nearly one billion people worldwide due to biodiversity loss, climate change, and declining agricultural sustainability. With the global population expected to reach approximately 9 billion by 2050, current agricultural systems face increasing pressure to ensure food and nutritional security. Furthermore, the productivity gains achieved during the Green Revolution are gradually diminishing due to climate variability and environmental stresses, highlighting the urgent need for crop varieties capable of sustaining higher yields under adverse conditions. Conventional plant breeding methods remain slow and labor-intensive, necessitating the adoption of advanced and efficient technologies. The growing availability of plant genome sequences has enabled the development of genome editing technologies that allow precise modifications at targeted genomic locations through sequence-specific nucleases that generate double-stranded breaks (DSBs), subsequently repaired via homology-directed repair (HDR) or non-homologous end joining (NHEJ) pathways. Among these technologies, the CRISPR-Cas system, originally identified as an adaptive immune mechanism in bacteria and archaea, has emerged as a powerful tool for targeted genome modification due to its simplicity, efficiency, and versatility.

Tools for genome editing

Minor genetic or epigenetic modifications in the genome can produce desirable traits such as improved yield, enhanced stress tolerance, and better storage ability in plants. Modern genome editing

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technologies enable controlled and precise alterations in plant genomes through gene editing or gene targeting, which involves permanent modification at specific genomic sites for crop improvement. The development of genome editing technologies depends on sequence-specific nucleases capable of inducing targeted DSBs at defined genomic locations. Engineered nucleases such as meganucleases, Zinc Finger Nucleases (ZFNs), Transcription Activator-Like Effector Nucleases (TALENs), and CRISPR-Cas systems have been widely employed in plant genome editing.

Zinc Finger Nucleases (ZFNs)

Zinc Finger Nucleases (ZFNs) are artificially engineered endonucleases composed of Zinc Finger Proteins (ZFPs) fused with the FokI restriction enzyme, enabling sequence-specific DNA cleavage. Each zinc finger recognizes a short DNA sequence of about three base pairs, allowing precise targeting of genomic regions . ZFNs function as dimers, where two monomers bind opposite DNA strands and allow the FokI domains to dimerize and create double-stranded breaks (DSBs) at specific locations.

Transcription Activator-Like Effector Nucleases (TALENs)

Transcription Activator-Like Effector Nucleases (TALENs) are engineered nucleases developed by fusing transcription activator-like effector (TALE) proteins with the FokI nuclease domain. TALE proteins originate from the bacterium Xanthomonas, where they naturally bind to host DNA and regulate gene expression during infection.

CRISPR/Cas System

The CRISPR/Cas system is an RNA-guided genome editing technology originally discovered as a natural defense mechanism in bacteria and archaea against viruses and plasmids . It consists of clustered repetitive DNA sequences (CRISPR) and associated Cas proteins that recognize and cleave foreign DNA. This system uses a guide RNA (gRNA) to direct the Cas9 endonuclease to a specific DNA sequence adjacent to a protospacer adjacent motif (PAM), enabling precise double-stranded DNA cleavage. The CRISPR/Cas mechanism operates through three stages—adaptation, expression, and interference—allowing targeted gene editing and mutation.

Mechanism of CRISPR/Cas System

The CRISPR/Cas system functions through three sequential steps: adaptation, expression, and interference. During adaptation, short fragments of foreign DNA known as protospacers are integrated into the CRISPR loci of the host genome, forming spacer sequences that serve as molecular memory of invading organisms. In the expression stage, these spacer sequences are transcribed into precursor CRISPR RNA (pre-crRNA) and processed into mature crRNA molecules.

Epigenetic Modifications

Epigenetic modifications regulate gene expression without altering the underlying DNA sequence through mechanisms such as DNA methylation, acetylation, and histone modification. The fusion of epigenetic modifier enzymes with nuclease-deactivated Cas9 (dCas9) has emerged as an effective approach for targeted epigenetic regulation in plants. These systems allow precise modification of DNA methylation patterns at specific genomic sites, thereby influencing gene expression levels.

Genome Editing in Vegetables

Vegetables are rich sources of vitamins, minerals, antioxidants, dietary fiber, and phytochemicals that contribute significantly to human health and food security. Reducing post-harvest losses and improving crop quality through genome editing has become essential for enhancing food availability and minimizing economic and nutritional losses along the supply chain. Genome editing technologies enable the rapid development of homozygous mutations without foreign DNA integration, facilitating the improvement of quality traits in major vegetable crops such as tomato and potato.

Genetic Engineering for Nutritional Enhancement and Shelf-Life

Nutritional Enhancement

Genetic engineering and genome editing technologies have played a significant role in improving nutritional quality traits in vegetable crops, particularly tomato. Fruit flavor and quality are closely associated with organic acid composition, and regulating these compounds can significantly improve organoleptic properties and consumer acceptance. Advances in omics technologies and quantitative trait loci (QTL) analysis have revealed strong genetic relationships between nutritional composition, fruit quality, and storage behavior in vegetable crops.

Shelf-Life Improvement

Postharvest losses in vegetables significantly reduce market value and nutritional availability, making shelf-life enhancement an important objective in vegetable crop improvement In vegetables such as tomato, postharvest treatments including UV-C irradiation have been reported to delay ripening, maintain fruit firmness, enhance antioxidant activity, and improve flavor quality.

Biotic and Abiotic Stress Resistance in Vegetable Crops

Abiotic Stress Resistance

Abiotic stresses such as drought, salinity, and high temperature significantly affect the growth, productivity, and quality of vegetable crops. CRISPR/Cas9 genome editing has been widely used to enhance stress tolerance in tomato by targeting specific stress-responsive genes. For example, editing of the SIMAPK3 gene has been associated with improved drought tolerance through reduction of oxidative stress damage. Similarly, modification of the SIAGL6 gene has improved tolerance to high-temperature stress and enhanced fruit quality.

Biotic Stress Resistance

Biotic stresses such as insects, bacteria, fungi, and viruses significantly reduce yield and quality in vegetable crops, making the development of disease-resistant varieties essential. The CRISPR/Cas9 genome editing system has been effectively used to enhance disease resistance in tomato by targeting key susceptibility and defense-related genes. For instance, inactivation of the DMR6 ortholog in Solanum lycopersicum resulted in improved resistance against multiple pathogens, including Xanthomonas, Phytophthora capsici, and Pseudomonas syringae, without causing adverse growth effects.

Challenges, Difficulties and Solutions in CRISPR/Cas9 for Vegetable Crops

The application of CRISPR/Cas9 in vegetable crops faces several major challenges that limit its wide adoption. A key limitation is the lack of complete genome information for many vegetable species, which restricts target identification and reduces the applicability of genome editing in such crops. Regulatory uncertainty also limits the application of CRISPR/Cas9 in vegetable improvement, as many countries still regulate genome-edited crops under traditional GMO frameworks (SDN-1, SDN-2, SDN-3), leading to overregulation and slow commercialization. To overcome these limitations, improved transformation protocols, especially for recalcitrant vegetable crops, are required.

Conclusion

Genome editing using CRISPR/Cas9 offers a precise and rapid alternative to conventional breeding for improving vegetable crops, which often suffer from limited genetic variability and slow breeding cycles. However, its full potential is restricted by insufficient genomic resources, inefficient transformation systems, and regulatory barriers. Despite these challenges, advances in sequencing technologies, improved gene delivery methods, and DNA-free editing approaches are gradually overcoming these limitations. Therefore, with the development of efficient protocols and supportive regulatory frameworks, CRISPR/Cas9 holds strong potential for enhancing yield, quality, and post-harvest traits in vegetable crops to meet future food security demands.

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Healthy Soil, Healthy Plate: Where Nutrition Truly Begins

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Healthy soil is the foundation of nutritious food and human well-being, though its role in food quality is often overlooked. This article provides an overview of how soil health influences crop nutrition, food quality, and human health through the soil–plant–human continuum. Healthy soils rich in nutrients, organic matter, and microbial diversity support plant growth and improve nutritional quality. Essential minerals such as zinc, iron, selenium, calcium, and magnesium move from soil into crops and ultimately into human diets, influencing growth, immunity, and health. The article also highlights the effects of soil on food quality, safety, and flavor, while discussing soil degradation, contamination, hidden hunger, and sustainable management practices for ensuring food security and improved nutrition.

Introduction: Food Begins Beneath Our Feet

When we think about nutritious food, we often focus on vegetables, fruits, grains, or supplements, rarely considering the soil beneath them. Yet, nutrition begins underground in a living system rich in minerals, organic matter, microbes, water, and air. Healthy soil forms the foundation of food quality by supplying essential nutrients that move from soil to plants and eventually to human diets. For centuries, farming communities recognized that fertile land produced healthier crops and healthier people. However, modern agriculture increasingly emphasized yield over soil health, contributing to hidden hunger despite record food production. According to the World Health Organization, nearly two billion people suffer from micronutrient deficiencies even when calorie intake is sufficient (Elegbeleye *et al.,* 2025). Nutrient-poor soils often produce nutrient-deficient crops, affecting human health and well-being. Therefore, understanding the connection between soil and nutrition is essential for improving food quality, combating malnutrition, ensuring food security, and building a healthier future (Figure 1).

Figure 1: The Soil–Plant–Human Continuum: Investigating the Impact of Soil Health on Nutritional Quality, Food Security, and Human Well-Being

Understanding Healthy Soil

Before understanding how soil shapes nutrition, we must first understand what makes soil healthy. Although the terms *soil* and *dirt* are often used interchangeably, they are fundamentally different. Dirt is lifeless material, whereas soil is a living, dynamic ecosystem capable of supporting plants, animals, and humans while maintaining environmental quality. Healthy soil is far more than a medium for anchoring plant roots; it is a complex system where minerals, organic matter, water, air, and living organisms interact continuously to sustain life. Several characteristics define healthy soil. It contains adequate nutrients in plant-available forms, sufficient organic matter to improve fertility, balanced pH for proper nutrient uptake, and good aeration and water-holding capacity. Healthy soil also supports rich biological activity, with billions of microorganisms that recycle nutrients and maintain soil fertility while minimizing contamination from harmful substances. Importantly, soil is not merely inert matter—it is a living ecosystem (Hohl and Verma, 2009). A single teaspoon of healthy garden soil contains more microorganisms than there are people on Earth (Pavlis, 2020). These microscopic organisms drive nutrient cycling, improve soil structure, and play an essential role in producing healthy, nutritious food.

Soil as the Foundation of Plant Nutrition

Plants are remarkable natural chemists that convert sunlight, water, and carbon dioxide into energy through photosynthesis. However, sunlight alone cannot produce healthy and nutritious crops. Plants rely on soil to obtain essential mineral nutrients required for growth, development, and food quality. Through their roots, they absorb at least 17 essential elements, including macronutrients, secondary nutrients, and micronutrients. Macronutrients such as nitrogen, phosphorus, and potassium promote plant growth, root development, energy transfer, and resistance to diseases. Secondary nutrients like calcium, magnesium, and sulphur support cell structure, chlorophyll formation, and protein synthesis. Micronutrients, including zinc, iron, copper, boron, and selenium, though needed in small quantities, are vital for plant and human health. Beneficial fungi called mycorrhizae often assist plants in nutrient uptake. These nutrients move into grains, fruits, vegetables, and seeds, becoming part of human diets. Therefore, healthy soil ensures healthy crops and ultimately supports human nutrition and well-being.

From Soil Nutrients to Human Nutrition

The relationship between soil health and human health is measurable, predictable, and, in many cases, preventable. Although food reaches people through farms, markets, and kitchens, many of the minerals essential for human survival begin their journey in the soil. Plants absorb nutrients from the soil through their roots, and these nutrients are transferred into grains, fruits, vegetables, and pulses consumed by humans. When soils are deficient in essential nutrients, crops grown in those soils often become nutrient-poor, eventually contributing to deficiencies in human diets. This direct relationship forms the basis of the soil–plant–human health continuum, emphasizing that human nutrition fundamentally begins beneath the soil surface.

One of the most significant examples of this connection is zinc deficiency, one of the world's most widespread micronutrient disorders. Soils lacking sufficient zinc frequently produce cereals with reduced zinc concentrations. Since cereals constitute staple foods for much of the global population, zinc deficiency becomes common, especially among children and pregnant women (Rahman and Das, 2025). Zinc plays a critical role in enzyme activity, immune system functioning, wound healing, cellular growth, and normal development. According to the World Health Organization (WHO), zinc deficiency contributes to over 400,000 child deaths annually, particularly in regions where dietary zinc intake remains inadequate (Liberato *et al.,* 2015). Children suffering from zinc deficiency commonly experience stunted growth, weakened immunity, delayed development, and increased vulnerability to infectious diseases.

Iron deficiency presents another major challenge linked to soil fertility. Iron-deficient soils often produce crops containing lower iron concentrations, increasing the risk of anemia, chronic fatigue, reduced work productivity, impaired cognitive development in children, and higher maternal mortality. Despite widespread supplementation and food fortification programs, iron deficiency anemia remains the most prevalent nutritional disorder globally, affecting more than 1.6 billion people, especially women and children dependent on cereal-based diets (Yunus, 2020).

Selenium deficiency further illustrates the importance of soil chemistry in human health. Selenium levels differ considerably among regions due to geological and environmental variations. In countries such as China, Finland, and New Zealand, selenium-poor soils historically resulted in crops with very low selenium content, increasing susceptibility to weakened immunity, cardiovascular diseases, thyroid dysfunction, and poor antioxidant defence. Conversely, selenium-rich soils support stronger immunity and healthier populations.

Other soil-derived nutrients are equally essential. Calcium-deficient soils may lower the nutritional quality of vegetables and legumes, indirectly affecting bone strength, muscle function, and nerve signalling. Magnesium depletion in soils can reduce food quality and influence hundreds of enzyme-mediated reactions in the human body. Copper deficiency interferes with iron metabolism and immune function, while boron affects plant reproduction and indirectly influences crop nutritional value.

This global challenge is often described as "hidden hunger," where people consume enough calories but remain deficient in vital micronutrients. Nearly two billion people worldwide suffer from deficiencies of iron, zinc, iodine, and vitamin A. Therefore, sustainable solutions such as balanced fertilization, micronutrient management, biofortification, organic matter restoration, and biologically active soils are essential for producing nutrient-rich crops and healthier populations.

Does Soil Affect Food Taste and Quality?

Beyond providing basic nutrition, soil strongly influences the sensory qualities of food, including flavor, aroma, texture, sweetness, and overall eating experience. The noticeable difference between a tomato grown in fertile garden soil and one produced commercially often reflects the role of soil in determining food quality. Scientifically, soil affects taste and aroma through several interconnected mechanisms. Nutrient availability regulates the production of volatile organic compounds that create distinctive flavors and fragrances in crops. Potassium, for example, enhances sugar synthesis and aromatic compounds in fruits, while balanced soil moisture helps maintain desirable sugar-to-acid ratios essential for flavor development. Soil microorganisms further contribute by producing compounds that plants transform into flavor-related molecules.

A clear example can be observed in aromatic rice varieties of Southeast Asia. Basmati rice from India and Pakistan, jasmine rice from Thailand, and other premium rice types develop their characteristic fragrance only when cultivated in specific soils; the same genetic variety grown elsewhere often produces inferior aroma and taste. Likewise, tea quality is heavily influenced by soil properties such as acidity, mineral composition, and organic matter, explaining differences between Darjeeling and Assam tea. The French concept of *terroir* captures this relationship, emphasizing how soil, climate, and farming practices together create distinctive food qualities, making healthy soils essential not only for nutrition but also for flavor and food diversity (Parker, 2015).

The Hidden Workforce: Soil Microorganisms

Beneath the soil surface exists a vast hidden community of microorganisms that continuously supports soil fertility and plant growth. Healthy soil contains billions of bacteria, fungi, protozoa, nematodes, and other microbes that together form the soil food web, carrying out essential biological functions beyond the ability of plants alone. One of their most critical roles is nutrient cycling. Although nitrogen constitutes nearly 78% of Earth's atmosphere, plants cannot use atmospheric nitrogen directly. Beneficial bacteria such as *Rhizobium*, associated with leguminous crops, and free-living *Azotobacter* convert atmospheric nitrogen into plant-available forms, naturally improving soil fertility and reducing fertilizer dependence (Rahman and Das, 2025). Similarly, mycorrhizal fungi help overcome phosphorus limitations by extending thread-like structures beyond plant roots, enabling access to phosphorus and water unavailable in surrounding soil. Nearly 80% of terrestrial plants depend on such associations. Other microorganisms decompose organic matter, solubilize phosphorus, suppress diseases, and stimulate growth. However, excessive tillage, monocropping, and chemical overuse can damage these beneficial microbial communities, making soil biological restoration essential for sustainable agriculture and human nutrition.

Soil Degradation: A Threat to Nutritious Food

Agricultural soils worldwide are degrading at an alarming pace despite growing awareness of soil health. The United Nations estimates that nearly one-third of global soils are moderately to highly degraded, while around 24 billion tons of fertile topsoil are lost annually through erosion (Rahman and Das, 2025). Since topsoil contains most nutrients, organic matter, and beneficial microorganisms, its loss directly reduces soil fertility and crop quality. Continuous harvesting without balanced nutrient replenishment causes nutrient depletion, gradually lowering productivity. Excessive use of synthetic fertilizers, especially nitrogen, may worsen soil degradation through acidification, microbial imbalance, and nutrient dilution, where crops appear productive but contain fewer minerals. Additional threats include salinity, declining organic matter, heavy metal contamination, and climate change–driven erosion, droughts, and floods. Consequently, higher yields may not always ensure healthier, nutrient-rich food.

Soil Contamination and Food Safety

From a food science perspective, soil acts as both a source of nutrients and a potential pathway for contaminants into food. While healthy soil supplies essential minerals, contaminated soils may transfer harmful substances into crops through the same soil-to-plant pathway. Heavy metals are among the most serious concerns. Cadmium, a toxic metal and known carcinogen, can accumulate in crops such as leafy vegetables, potatoes, and grains, often originating from phosphate fertilizers containing cadmium impurities. Lead contamination, though reduced after the phaseout of leaded gasoline, persists in urban and roadside soils and poses severe risks to children, particularly affecting cognitive development. Arsenic presents another challenge, especially in flooded rice-growing systems where paddy rice absorbs arsenic more efficiently, increasing chronic exposure risks in rice-consuming populations (Rahman and Das, 2025). Pesticide residues may also persist in soils and enter root and leafy vegetables. Since soil-derived contaminants become integrated into plant tissues, they cannot easily be removed through washing or cooking. ***The message is clear: safe food starts with safe soil.*** Regular soil testing, contamination prevention, and responsible land management are essential to protect food quality and human health.

Building Healthy Soil for Healthy Food

The encouraging reality is that degraded soils can be restored through proper management and sustainable agricultural practices. Healthy soil develops gradually through continuous interaction among farmers, soil organisms, and the surrounding environment. One of the first steps in soil restoration is soil testing, which helps determine nutrient status, soil pH, organic matter content, and possible contamination. Understanding soil conditions allows farmers to apply nutrients more precisely, preventing both deficiencies and excessive fertilizer use. Balanced fertilization is equally important for maintaining productivity and soil health. Nutrients should be supplied in appropriate amounts and combinations rather than through indiscriminate fertilizer application. Combining synthetic fertilizers with organic sources such as compost, farmyard manure, crop residues, and biofertilizers improves nutrient efficiency and long-term sustainability. Organic amendments restore soil organic matter, improve water retention, and stimulate beneficial microbes. Cover crops reduce erosion and enrich soil fertility, while crop rotation balances nutrient demands and suppresses pests. Conservation agriculture and biofortification further strengthen soil health, ultimately producing resilient crops and more nutritious food for future generations.

Soil Health and Food Security

With the global population projected to approach 10 billion by 2050, ensuring adequate and nutritious food for all presents a major challenge. Climate change, water scarcity, and shrinking agricultural land further intensify this problem, making soil health essential for long-term food security. Healthy soil contributes to food security in several ways. First, it improves crop productivity, often producing 10–30% higher yields than degraded soils due to better fertility, structure, and biological activity (Brevik, 2010). Second, healthy soils enhance nutritional quality, producing crops richer in essential vitamins and minerals, thereby helping address hidden hunger. Third, soils rich in organic matter provide climate resilience by storing more water during droughts and improving drainage during heavy rainfall, reducing crop failure risks. Fourth, healthy soils reduce dependence on expensive external inputs such as fertilizers, pesticides, and irrigation, lowering farming costs and environmental impacts. Finally, healthy soils sustain rural livelihoods by maintaining long-term agricultural productivity. Therefore, investing in soil health through research, farmer education, and sustainable management practices is not merely an agricultural priority—it is essential for public health, climate resilience, and global food security.

Conclusion

The journey from farm to nutrition begins beneath our feet—in healthy soil. The nutritional quality, flavor, and safety of food largely depend on soil health, which supports plant growth, nutrient availability, and microbial activity. Healthy soil nourishes crops, and crops, in turn, nourish people. However, soil degradation, contamination, and poor management increasingly threaten food quality and human nutrition. Sustainable practices such as balanced fertilization, organic matter management, crop rotation, and soil conservation can restore degraded soils and improve food systems. Protecting soil health is therefore not only an agricultural responsibility but also a public health necessity. Simply put, ***healthy soil and healthy food are inseparable—nutrition truly begins in the soil.***

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Insect Pest Management and its Effect on Unseen, Silent Insect

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Insurance pest management is the study or concern about the effect of insecticide on non target organism, environment and its solutions

Our chemical insecticides are still non-specific, with broad activity on a wide range of target and non-target organisms. Some classes of insecticides have emerged that are more selective (e.g., insect-growth regulators, Bt toxins), but the expectation of "selective insecticides" that was articulated in one of the original descriptions of IPM largely remains elusive in modern pest management.

Our current insecticide options, it remains a challenge to strike the delicate balance between safeguarding food production and human health while avoiding deleterious effects upon the wider environment—these are commonly grouped under the inclusive term "non-target effects."

The goal of this seminar is to consider whether current agricultural use of neonicotinoids, the most popular class of insecticides in the world, is achieving this balance. For this assessment, we focus primarily on U.S. agriculture where most of the principal crops are routinely grown from neonicotinoid-treated seed.

We review neonicotinoid use patterns, their potential for effective pest management and subsequent yield benefits. then discuss the potential for non-target effects.

- We discuss the potential for nontarget effects. Because neonicotinoids are highly water soluble, aquatic environments have proven to be an environmental sink for these compounds
- we discuss some of the observed non-target impacts of neonicotinoids upon aquatic communities, and whether these negative effects matter in a broader context.

Neonicotinoids

- Neonicotinoids are a group of insecticides with a chemical structure that is similar to nicotine.
- Class of neuro active insecticides
- Similar to nicotin
- Newest major class of insecticides
- Replaced organophosphates and carbamates insecticide.
- Developed from nitromethelene compounds
- The neonicotinoid Imidacloprid is currently the most widely used insecticide in the world
- Used extensively in agriculture
- Similar to that of natural nicotine.
- Act as antagonists at the postsynaptic nicotine acetylcholine receptor (nAChR) In the central nervous system.
- Neonicotinoides possess contact and systemic activity.
- Some example of Neonicotinoids
  - ➢ 1^{st} generation- Imidacloprid, Acetamiprid, clothianidin
  - ➢ 2^{nd} generation- Thiamethoxam
  - ➢ 3^{rd} generation- Nithiazin, Nintenpyram

Surveying the current insecticide landscape in the United States reveals that a single class of compounds, the Neonicotinoids, clearly stands above the others in terms of both the prevalence of use on the landscape and in terms of their potential toxicity to insects.

Compared to older classes of insecticides, neonicotinoids were more selective because of their

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systemic nature, (it was thought that only insects feeding on the crop would be exposed) and their apparently lower toxicity to mammals and other vertebrates. majority of use is as coatings on seeds of annual crops, principally corn, soybeans, cotton, and wheat. These compounds are used on every hectare of corn planted in the United States, and that the amount of active ingredient applied to corn seeds doubled between 2011 and 2014.

There are also use on seeds of soybeans, cotton and other crop. It is important to note that these trends have been documented even as transgenic hybrids—Bt corn and cotton. current insecticide use rates far exceed the <50% of corn acres and <10% of soybean acres that were typically treated with an insecticide from the 1950s to the 1990.

when patterns of insecticide use were dictated primarily by the same key pests that are now largely controlled by transgenic hybrids. There are no longitudinal datasets to cite on pest trends over that time, but recent reviews reflect that most of the target pests listed for neonicotinoid seed treatments in registration and marketing materials were never common, are not more common now, and usually do not cause significant yield loss when they are present.

In other words, rather than "replacing" older insecticide classes with neonicotinoids, the seed-treatment approach fostered by neonicotinoids has created an entirely new and exceptionally convenient way to deliver insecticides without regard for documentation or monitoring of actual pest infestations on the most widely grown commodities in the U.S.

Realized Potential Of Neonicotinoid-Treated Seeds For Pest Management And Yield Protection In Field Studies

- If a specific pest management tool provides high benefits to agriculture at large, some level of collateral damage to the surrounding environment may be deemed acceptable. Non-target effects are somewhat inevitable, and perhaps to be expected, in agricultural systems that rely heavily upon large, intensive monocultures and regular deployment of a suite of pesticides.
- A survey of the literature reveals no convincing or consistent demonstrations of economic benefits associated with neonicotinoid use in grain and oilseed crops. Small-plot field studies throughout North America, analyses of trials in soybeans over multiple U.S. states and multi-year larger scale trials conducted across dozens of commercial corn and soybean fields have all failed to detect clear or consistent economic benefits attributable to this widespread approach to pest management.
- Surveys of pest infestations over several years in intensive corn and soybean producing area of Quebec and Ontario, Canada found that neonicotinoids had potential to protect yield in <5–8% of cases. Populations of target pests were also documented in these studies and were low (often zero)— leading the authors to conclude that no pest management benefit was realized since pests were not present at damaging levels.

The Fate of Neonicotinoids From Seed Coatings

- The very properties that make neonicotinoids ideally suited for use as seed treatments—high water solubility and the potential for xylem transport in plant tissues—ensure that the majority of the neonicotinoid applied to crop seeds.
- neonicotinoids deployed more widely and thoroughly than annual production of corn, or maize in the United States, where virtually every non-organic seed grown for grain production is treated with thiamethoxam and/or clothianidin, and less commonly, imidacloprid.
- During planting of corn seeds, neonicotinoids and other active ingredients are abraded from the seed coat and exhausted via pneumatic planting equipment typically used in modern North American planting operations. This dust moves

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out into the surrounding landscape exposure via insecticide drift that has resulted in reports of honey bee mortality in multiple jurisdictions.

- Active ingredient was found to have potential for lethal and sub-lethal effects extending hundreds of meters beyond each planted field, resulting in potential for lethal exposure of non-target organisms, in this case foraging honey bees.
- planting of treated seeds typically results in 2–3% of the active ingredient applied to seeds being abraded and dispersed during planting, although the authors note that this percentage may range as high as 12% of the applied active ingredient (Schaafsma et al., 2018).

Ecosystem-Wide Effects Of Insecticide Use: What's Past Is Prolog

- Sixty years ago, we were confronted with similar stories, but with different players; environmentalists, including author Rachel Carson, were alarmed by the negative ecosystem-wide effects of synthetic pesticides, especially the organochlorine insecticide, DDT. One of the key themes that made Carson's Silent Spring so influential was the connection she drew between environmental and human health.
- A recent example from Africa illustrates this connection clearly and highlights the likelihood of unanticipated ecological disruptions when pesticides enter aquatic systems. This study found that relatively low concentrations of the neonicotinoid imidacloprid and the organophosphate diazinon reduced abundance of some of the more sensitive aquatic insect species, leading to larger aquatic snail populations because of reduced competition for food and less predation from insect species

Concluding Thoughts

- Insecticide use in the U.S. Continued to increase after Silent Spring, and those increases continue today In the U.S., where Bt corn is rightly hailed as a target-specific and largely environmentally benign breakthrough in terms of reducing pesticide use, it is not common knowledge that virtually every kernel of Bt corn is treated with at least one neonicotinoid insecticide, and at steadily increasing levels.
- IPM was developed over 50 years ago as a response to a suite of non-target effects but remains all but abandoned in modern pest management in oilseed and grain crops grown in the U.S., notably corn, even while pest pressures are at or near historic lows.
- there is undoubtedly a need in the U.S. and elsewhere for wholesale changes in regulatory policy to address current and future unintended environmental consequences of pesticide use, a strategic approach to implement immediate change already exists: integrated pest management (IPM). If IPM is not re-embraced and use of neonicotinoids (and other pesticides) continues along the current trajectory, aquatic communities will continue to degrade.

There is abundant rationale to reintroduce the IPM approach—including the notion of simply not applying pesticides where pest densities are not sufficient to cause economic harm. This requires that monitoring of pests and use of thresholds—critical elements of IPM—be reintroduced to protect natural enemies communities that can provide biological control, one of the original goals of IPM.

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Rhizobium Biofertilizers: A Key approach to Sustainable Nitrogen Fixation in Agriculture

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Nitrogen fixation is the process by which atmospheric nitrogen is converted into a usable form that plants can utilize. This fixation is significantly enhanced by the symbiosis between Rhizobium and the root of leguminous plants. Rhizobium is basically a gram-negative bacterium that undergoes the process of nodule formation and other pathways that enhance nitrogen fixation. This article mainly emphasized the role of rhizobium in nodule formation, its isolation from the rhizosphere of the plant, its different methods of application, advantages, limitations, and different forms in which it is available to the farmers and also about some quality parameters for rhizobium.

Nitrogen is one of the most vital macronutrients present on the earth's surface and is essential for plant growth. It plays a key role in the synthesis of various components such as nucleic acids, proteins and amino acids. About 78.1 per cent of nitrogen is present in the Earth's atmosphere, but it is not directly accessible to the plants until it is converted into a usable form.

Biological nitrogen fixation is a natural process in which certain bacteria convert the atmospheric nitrogen into ammonia, the usable form in which plants adsorb and utilize the nitrogen. This process is especially important for legume plants, which live in association with nitrogen-fixing bacteria such as Rhizobium to fulfil the nitrogen requirements.

Rhizobium is a type of beneficial bacterium mainly found in the roots of legumes, soybeans, tobacco, and other nitrogen-demanding crops. This bacterium forms nodules on the roots of plants, where it carries out the process of nitrogen fixation. This symbiotic relationship between rhizobium and leguminous plants not only provides the nitrogen to the host plant but also increases the nitrogen content of the soil, which helps other crops to grow better

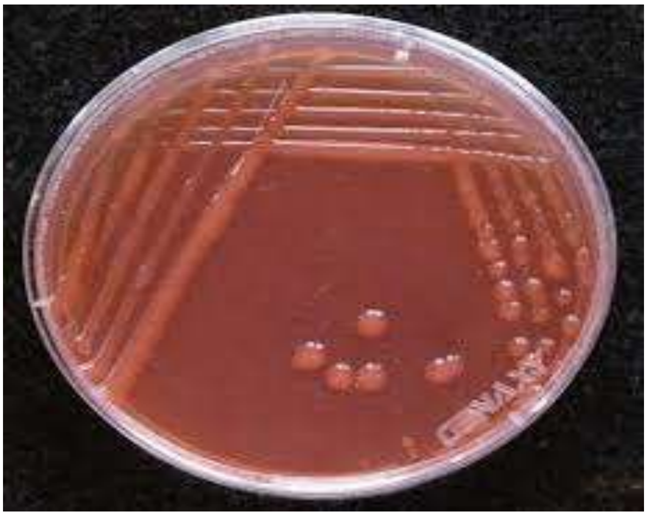
Isolation of Rhizobium from the roots nodules of leguminous plants

1. For the isolation of rhizobium, healthy and pink coloured nodules were selected.
2. Then thoroughly wash the nodules with running tap water for about 2-3 times to remove the soil particles. Further, nodules were washed with sterile distilled water.
3. Surface sterilisation of nodules was carried out by dipping them in 1% mercuric chloride for 30 seconds and then wash the nodules with sterile distilled water repeatedly for 4-5 times.
4. The nodules were then treated with 1% sodium hypochlorite solution for about 1 minute and after that wash the nodules with sterile distilled water repeatedly for 10 times.
5. Then nodules were thoroughly crushed in100 µl of 15% glycerol and then crushed using a sterilized mortar pestle and serial dilutions ranging from 10^{-1} to 10^{-10} were prepared.
6. From each dilution series, 100 µl of the suspension was spread onto Yeast Mannitol

ISSN: 3049-2289

Extract Agar medium using a sterile micropipette.

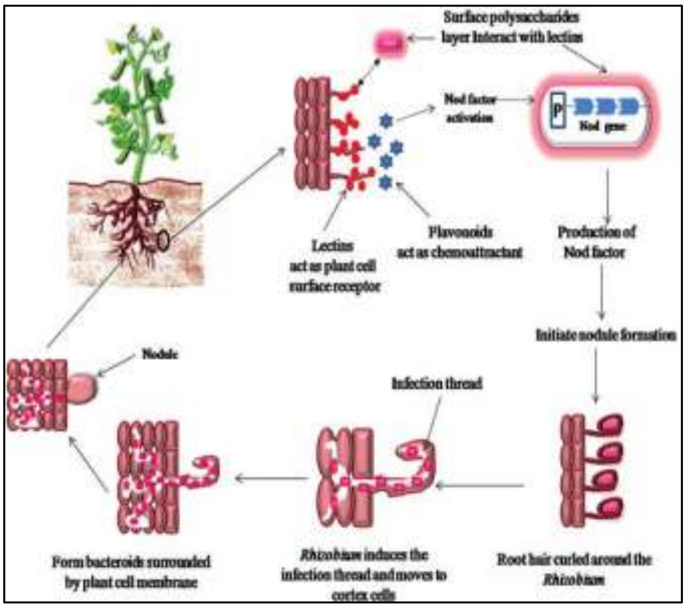
7. The medium was supplemented with itraconazole (200 mg/l) to suppress fungal growth, and the plates were incubated at 28 ± 2°C for two days. After incubation, individual colonies were selected and re-streaked for further purification.



Rhizobium isolated from the roots of leguminous plants

The Rhizobium-legume Symbiosis

The infection process of rhizobium in legume roots involves a well-coordinated series of interactions that begins when the roots of the plant release flavonoids into the soil. These flavonoids act as a chemoattractant and attract the bacteria towards the root surface. After that, the rhizobium bacteria get attached to the root hair. The bacterial surface polysaccharides interact with plant lectins present on root cells. These lectins act as a plant surface receptor, helping in recognition. Flavonoids activate the bacterial nod genes and these further produce the signaling molecules called nod factors, which trigger the nodule development. The nod factors cause the root hairs to curl around the bacteria and trap the bacteria inside. After curling, the plant forms the infection thread and rhizobium moves through this thread toward the root cortex cells. The bacteria stimulate the rapid division of cortical cells, which leads to the formation of a root nodule. Inside the nodule, rhizobium cells differentiate into bacteroids and are surrounded by the plant cell membrane. These bacteroids are mainly the nitrogen-fixing form of bacteria. Inside nodules, bacteroids convert atmospheric nitrogen (N2) into ammonia using the enzyme nitrogenase. The plant further uses this ammonia for growth and protein synthesis; the bacteria receive nutrients and shelter from the plant.



Different methods of application of Rhizobium

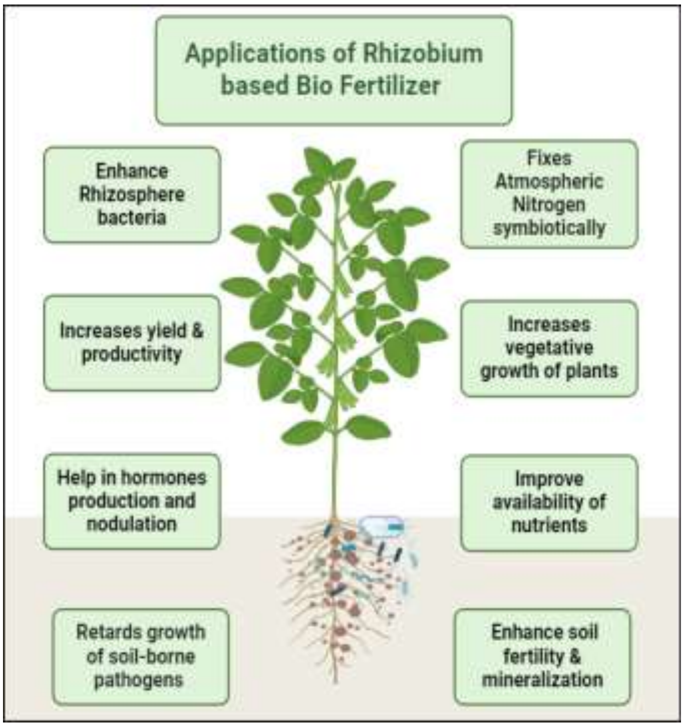
a) **Seed treatment:** It is the most common and widely accepted method due to the direct root contact. Firstly, prepare the slurry using rhizobium culture and a sticking agent like sugar solution. Then dip the seeds in the solution so that each seed gets properly coated. After that, dry the seeds in the shade before sowing. This method is cost-effective, easy to apply and ensures a high rate of nodulation.

b) **Soil application:** This method is mainly used in large-scale farming. In this method, mix the rhizobium inoculant with the farmyard manure or apply it directly near the root zone.

ISSN: 3049-2289

c) **Root dip method:** This method is mainly used in case of nurseries and transplanted crops. In this method, firstly, we will prepare the rhizobium suspension in water and then dip the seedlings into the solution before transplanting, which ensures early establishment.

Applications of Rhizobium based bio-fertilizer



Limitations of Rhizobium Biofertilizer

- **Environmental and soil factors affecting the performance of Rhizobium:** Low soil pH and poor soil fertility can negatively affect the establishment of effective symbiotic associations between legumes and rhizobia.
- **Slow response:** Biofertilizers act very slowly as compared to chemical fertilizers and may not provide immediate results.
- **Host specificity**: Different Rhizobium strains work only with specific legume crops, so the wrong strain may not be effective.
- **Sensitivity to environmental conditions:** High temperature, drought, soil acidity, salinity, or poor soil conditions can reduce bacterial survival and activity.
- **Financial and practical challenges limiting widespread adoption:** The high cost of developing and manufacturing quality inoculants can be a major limitation, particularly for small-scale farmers. Moreover, the proper use of inoculants requires adequate knowledge and specific management practices, which may not be accessible to all farmers.

Different forms in which the Rhizobium biofertilizer is available

Quality assessment parameters for Rhizobium-based biofertilizers as specified under government regulations: -

The quality evaluation criteria for Rhizobium and other approved biofertilizers are described in the Fertilizer (Control) Order, 1985, which also establishes the quality standards for these biofertilizers under the FCO, 1985.

1. **Instructions and labelling:** The product should clearly provide details regarding the strains of Rhizobium, compatible host plants, application methods, expiry date, storage requirements and maintenance conditions. Proper labelling ensures the correct usage of the biofertilizer and improves its overall effectiveness.
2. **pH:** It is the most important factor influencing the survival and efficiency of Rhizobium cells. For optimum performance, the pH range should be between 6 and 7.
3. **Carrier materials:** Sterile carrier materials should be used for Rhizobium cells, as they are essential for maintaining their activity and survival during application to seeds or soil.
4. **Moisture content:** The moisture level of the applied biofertilizer plays an important role in maintaining the survival of Rhizobium cells during storage, transportation and application. Excessive or insufficient moisture can reduce shelf life and negatively

affect the overall effectiveness of the biofertilizer.

Conclusion:

Rhizobium-based biofertilizers play a significant role in sustainable agriculture by enhancing biological nitrogen fixation and improving soil fertility in leguminous crops. They are available in different forms, such as carrier-based, liquid, and granular formulations, which provide flexibility for agricultural use. These biofertilizers can be applied through various methods, including seed treatment, seedling root dipping and soil application, depending on crop and field requirements. Their use reduces dependence on chemical fertilizers, promotes eco-friendly farming practices and supports better crop productivity. The effectiveness of these biofertilizers depends on several quality parameters such as viable cell count, pH, moisture content, carrier material, and proper storage and labelling conditions. Adherence to the quality standards prescribed under the Fertilizer (Control) Order, 1985 ensures the efficiency, shelf life and reliability of Rhizobium inoculants. Therefore, the proper production, handling and application of Rhizobium-based biofertilizers can contribute greatly to sustainable crop production and environmental conservation.

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Optimizing Micronutrient Management for Enhanced Fruit Crop Growth and Yield

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1.Introduction

Fruit crops are an essential component of global agriculture, contributing significantly to food security, human nutrition, and economic stability. To achieve optimal growth, yield, and fruit quality, plants require a balanced supply of both macronutrients and micronutrients. While macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are needed in large amounts, micronutrients are equally vital, albeit required in much smaller quantities. These trace elements including iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), boron (B), molybdenum (Mo), and chlorine (Cl) play crucial roles in various physiological and biochemical processes that directly influence plant metabolism, enzyme activation, chlorophyll synthesis, fruit development, and overall stress resistance. Deficiencies or imbalances of these elements can lead to reduced growth, poor fruit set, decreased yields, and inferior fruit quality, ultimately affecting market value and profitability for farmers.

Micronutrients function as essential catalysts in enzyme systems that regulate plant growth and development. For example, iron plays a pivotal role in chlorophyll formation and photosynthesis, while zinc is integral for hormone production and enzyme activation. Boron contributes to cell wall formation, pollen viability, and fruit set, ensuring proper reproductive success in fruit crops. Manganese is required for photosynthesis and nitrogen assimilation, and copper aids in lignin synthesis, which strengthens plant tissues and enhances resistance to diseases. Molybdenum, although required in trace amounts, is indispensable for nitrogen metabolism and biological nitrogen fixation in legumes. Chlorine, often overlooked, is essential for osmoregulation, water balance, and disease resistance in certain crops. Since these elements work synergistically, an imbalance or deficiency in one micronutrient can disrupt multiple physiological processes, leading to various growth disorders and reduced crop performance.

One of the critical challenges in modern fruit production is the variability in soil micronutrient availability, which depends on several factors, including soil type, pH, organic matter content, and climatic conditions. Highly weathered or calcareous soils often exhibit micronutrient deficiencies due to reduced solubility and limited root uptake. Excessive application of macronutrients, such as phosphorus, can interfere with the absorption of micronutrients like zinc and iron, exacerbating deficiency symptoms. Waterlogged conditions, soil compaction, and poor microbial activity further hinder nutrient availability and uptake. Therefore, efficient micronutrient management strategies are essential to ensure fruit crops receive adequate nutrition for optimal growth and yield.

The increasing demand for high-quality fruits necessitates improved nutrient management techniques that go beyond traditional fertilization practices. Modern approaches such as soil and leaf tissue analysis, precision agriculture, foliar applications of micronutrients have proven effective

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in addressing deficiencies and integrating organic amendments such as compost, biofertilizers, and microbial inoculants can enhance soil fertility and promote sustainable nutrient cycling. Research into nanotechnology-based fertilizers and slow-release micronutrient formulations also offers promising solutions for improving nutrient use efficiency and reducing environmental impact. By understanding how these elements contribute to fruit crop physiology, farmers and agricultural professionals can implement targeted interventions to enhance yield quality, improve stress tolerance, and promote sustainable agricultural practices.

2. Essential Micronutrients and Their Functions

Micronutrients are essential elements required in small quantities by fruit crops but play a crucial role in plant growth, development, and productivity. These nutrients include iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), boron (B), molybdenum (Mo), and chlorine (Cl), each of which performs specific physiological and biochemical functions. Iron (Fe) is vital for chlorophyll synthesis and electron transport in photosynthesis, preventing chlorosis and poor plant development. Zinc (Zn) is essential for enzyme activation, protein synthesis, and auxin production, promoting fruit set and seed formation. Copper (Cu) facilitates lignin formation, strengthens plant cell walls, and aids in enzymatic reactions related to respiration and photosynthesis. Manganese (Mn) plays a significant role in nitrogen metabolism, oxidation-reduction processes, and chlorophyll production, ensuring proper leaf expansion and disease resistance. Boron (B) is crucial for cell wall stability, pollen germination, sugar transport, and fruit quality, preventing disorders such as fruit cracking and poor seed formation. Molybdenum (Mo) is required for nitrogen fixation and nitrate reduction, enabling plants to utilize nitrogen efficiently. Chlorine (Cl) contributes to osmotic regulation, stomatal function, and disease suppression, supporting overall plant health. Deficiencies of these micronutrients can lead to severe physiological disorders, reduced yield, and poor fruit quality. Their availability in soil is influenced by factors such as soil pH, organic matter content, and interactions with other nutrients. Therefore, efficient micronutrient management through soil amendments, foliar applications, and precision agriculture techniques is crucial for enhancing fruit production and ensuring sustainable agricultural practices.

3. Micronutrient Management Strategies

Efficient micronutrient management is essential for ensuring optimal growth, yield, and fruit quality in crops. Since micronutrient availability in the soil is influenced by factors such as pH, organic matter, and interactions with other nutrients, different application methods are employed to address deficiencies effectively.

3.1 Soil Application Methods (Chelates, Granules, and Fertilizers)

Soil application is a widely used method for supplying micronutrients to fruit crops. Micronutrients can be applied in different forms, such as inorganic salts (e.g., zinc sulfate, borax), chelated compounds (e.g., EDTA-chelated iron, Zn-EDTA), and slow-release granules. Chelates are highly effective because they prevent micronutrients from binding with soil particles, ensuring better plant uptake. Granular fertilizers, often mixed with macronutrients, provide a slow and steady release of micronutrients. In highly alkaline or calcareous soils, where micronutrient availability is limited, chelated forms are preferred to prevent nutrient fixation and improve uptake efficiency.

3.2 Foliar Spray Techniques and Timing for Maximum Absorption

Foliar application is a rapid and effective method for correcting micronutrient deficiencies, especially in conditions where soil availability is limited. Nutrients are absorbed directly through leaf stomata, allowing for quick assimilation into metabolic processes. The effectiveness of foliar sprays depends on factors such as droplet size, application time, and nutrient concentration. Spraying should be done during the early morning or late evening to prevent evaporation loss and maximize absorption. Micronutrients such as zinc, iron, and boron respond well to foliar feeding, particularly during critical growth stages like flowering and fruit set. Repeated applications at lower concentrations are more effective than single high-dose treatments.

3.3 Organic Sources of Micronutrients (Compost, Manure, Biofertilizers)

Organic amendments such as compost, manure, and biofertilizers play a significant role in improving micronutrient availability in the soil. Compost and farmyard manure enhance soil structure, increase microbial activity, and release micronutrients gradually. Biofertilizers, such as mycorrhizal fungi and nitrogen-fixing bacteria, improve nutrient solubilization and root uptake. Organic sources also promote soil biodiversity, reduce dependency on synthetic fertilizers, and enhance long-term soil fertility. The incorporation of crop residues and green manures further enriches soil with essential micronutrients.

3.4 Precision Agriculture and Micronutrient Delivery Systems

Advancements in precision agriculture have revolutionized micronutrient management through site-specific nutrient applications. Technologies such as remote sensing, soil testing, and GPS-guided variable rate application (VRA) help optimize micronutrient distribution based on crop needs. Nanotechnology-based fertilizers and controlled-release formulations ensure efficient nutrient uptake while reducing environmental losses. Drip irrigation systems infused with micronutrient solutions provide targeted delivery, improving nutrient-use efficiency and minimizing wastage. These modern approaches enhance sustainability and ensure balanced nutrition for fruit crops.

Conclusion

Micronutrients play a pivotal role in ensuring optimal growth, yield, and fruit quality in crops, despite being required in trace amounts. Deficiencies in elements like iron, zinc, boron, and manganese can lead to significant physiological disorders, reduced productivity, and poor marketability of fruits. Effective management strategies including soil applications, foliar sprays, organic amendments, and precision agriculture techniques are essential for addressing micronutrient imbalances. Chelated fertilizers enhance uptake in problematic soils, while foliar feeding provides rapid correction during critical growth stages. Organic sources improve long term soil health, and advanced technologies like nano-fertilizers and precision delivery systems optimize nutrient efficiency. By adopting these integrated approaches, farmers can enhance fruit crop performance, improve stress resilience, and promote sustainable agricultural practices. Continued research and innovation in micronutrient management will further refine these strategies, ensuring food security and economic viability for fruit growers worldwide.

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Sustainable Agricultural Practices for Enhanced Fruit Quality

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Introduction

The increasing demand for high quality fruits, driven by consumer preferences and global food security concerns, has highlighted the importance of sustainable agricultural practices. Sustainable fruit production focuses on optimizing yield and quality while preserving natural resources, maintaining soil health, and reducing environmental impact. Unlike conventional farming, which often relies heavily on chemical inputs and intensive land use, sustainable practices integrate eco-friendly approaches such as organic fertilization, integrated pest management, efficient water use, and biodiversity conservation. By adopting sustainable methods, farmers can enhance fruit quality, extend shelf life, and improve the nutritional value of produce, making it more desirable in competitive markets.

One of the fundamental pillars of sustainable fruit production is soil health management. Healthy soils provide essential nutrients, support beneficial microbial activity, and enhance water retention, all of which are crucial for fruit development. Practices such as crop rotation, cover cropping, compost application, and reduced tillage help maintain soil structure and fertility while minimizing erosion and degradation. The use of biofertilizers and organic amendments enhances nutrient availability, reducing dependence on synthetic fertilizers that contribute to soil depletion and pollution. By ensuring a balanced supply of nutrients, these practices promote optimal fruit growth, better flavor, improved texture, and higher resistance to diseases.

Water conservation and climate-smart agriculture also play a crucial role in sustainable fruit production. Techniques such as drip irrigation, rainwater harvesting, and mulching reduce water wastage and enhance moisture retention in the soil, ensuring consistent fruit development. Furthermore, agroforestry and polyculture systems support biodiversity, which naturally regulates pests and improves ecological balance. The integration of precision agriculture, including remote sensing and data-driven nutrient management, further enhances resource efficiency while minimizing chemical runoff and environmental degradation. By implementing these strategies, farmers can produce high-quality fruits while maintaining environmental integrity and long-term agricultural productivity.

Sustainable Agricultural Practices for Enhanced Fruit Quality:

Enhancing fruit quality while reducing adverse environmental effects and guaranteeing the long term viability of farming systems are all made possible by sustainable agriculture techniques. By enhancing biodiversity, lowering chemical inputs, and improving overall ecosystem health, these techniques aim to maximize resource usage. Here's a detailed overview of sustainable agricultural practices for enhanced fruit quality:

Organic Farming:

- Due to the lack of external inputs like mineral fertilizers or pesticides, organic farming is meant to be ecologically beneficial. Natural inputs and methods, such as composting, cover crops, and biological pest management, are emphasized in organic farming. Artificial pesticides and fertilizers should be avoided to limit fruit chemical residues and support healthier ecosystems. According to studies, organic farming can result in fruits having greater concentrations of antioxidants and other beneficial compounds.

Agroforestry:

- Agroforestry has gained worldwide recognition over the past three decades as an integrated strategy for sustainable land use due to its advantages in terms of output and the environment. Incorporating trees with crops offers a variety of advantages, including improved soil structure, increased water retention, and habitat for beneficial creatures. Fruit crops benefit from increased nutrient availability in agroforestry systems, which enhances fruit quality and flavor.

Climate-Smart Agriculture:

- Climate-smart agriculture is a strategy for changing and reorienting agricultural systems to ensure food security in light of the new realities of climate change. The effects of climate change on fruit production can be lessened by adapting agricultural methods to changing climatic conditions. Techniques like choosing heat-tolerant varieties and altering planting times help protect fruit quality in the face of temperature and precipitation changes.

Agroecology and Biodiversity:

- **Polyculture and Crop Rotation:** A polyculture is a method for growing several crops simultaneously, in the same area, and at the same time. Planting a variety of crops in one location encourages organic pest management, lowers the likelihood of illness, and improves soil fertility. Crop rotation with different species helps break pest and disease cycles.
- **Cover Crops:** Planting cover crops in between rows of fruit reduces soil erosion, strengthens soil structure, and provides organic matter, all of which increase the availability of nutrients to plants.
- **Hedgerows and Buffer Strips:** By establishing natural vegetation along field boundaries, you may increase pollination and pest management by providing habitats for beneficial birds, insects, and other wildlife.

Soil Health Management:

- **No-Till or Reduced Tillage:** By minimizing soil disturbance, soil structure is maintained, erosion is decreased, and water-holding capacity is increased. Additionally, it supports advantageous soil microbes that contribute in nitrogen cycling.
- **Composting and Organic Matter Addition**: Applying compost and organic materials improves soil fertility, water retention, and microbial activity, which results in healthier plants and better-quality fruit.
- **Mulching:** The term "mulch" refers to any substance other than soil or living vegetation that serves as a permanent or semi-permanent protective layer over the soil surface. Applying organic mulch (such as straw or wood chips) over fruit plants lowers weed competition, retains soil moisture, and regulates soil temperature.

Integrated Pest Management (IPM):

- **Biological Control:** Despite experiencing fluctuating levels of popularity throughout the past century, the use of living organisms as pest control agents is now firmly established as a crucial part of integrated pest management. The use of chemical pesticides is decreased by introducing natural predators and parasitoids to manage pests. For example, releasing ladybugs to control aphids.

ISSN: 3049-2289

- **Trap Crops:** Trap crops are plants grown along with the main crop in order to manipulate insect behaviour to manage the insect pests and are used as a cultural management strategy in several crops. Planting specific crops that attract pests away from fruit crops can help protect the main crop while supporting natural pest control.
- **Pheromone Traps:** Monitoring and using pheromone traps for pest detection and control help reduce the reliance on broad-spectrum pesticides.

Water Management:

- **Drip Irrigation:** Drip irrigation is the slow, even application of low-pressure water to soil and plants using plastic tubing placed near the plants' root zone. It is an alternative to sprinkler or furrow methods of irrigating crops. Drip irrigation can be used for crops with high or low water demands. Efficient water delivery through drip systems minimizes water wastage and reduces disease spread by keeping foliage dry.
- **Rainwater Harvesting:** Collecting rainwater for irrigation reduces reliance on freshwater sources and conserves water resources.

Nutrient Management:

- **Precision Fertilization:** Using soil tests to tailor nutrient application ensures that plants receive the right amount of nutrients, minimizing excess that could harm the environment.
- **Leguminous Cover Crops:** Leguminous cover crops may fix nitrogen in the soil, eliminating the requirement for chemical fertilizers.

Climate-Resilient Practices:

- **Plant Selection:** Choosing fruit varieties that are well-suited to the local climate and have better disease resistance and tolerance to extreme weather events.
- **Microclimate Management:** Using shade nets, windbreaks, and other structures to modify the microclimate can protect fruit crops from adverse weather conditions.

Post-Harvest Management:

- **Proper Harvest Timing:** Fruits with higher flavor, texture, and nutritional value are harvested at the proper stage of ripeness.
- **Cold Storage and Controlled Atmosphere:** Fruits' shelf lives can be extended using cold storage and controlled environment technologies without the need of a lot of chemical preservatives.

Community Engagement and Education:

- **Farmers' Training:** Giving farmers education and training in sustainable methods encourages better understanding and implementation of these practices.
- **Consumer Awareness:** Consumers may generate demand for such goods and help market-driven sustainability by being informed about the advantages of sustainably produced fruits.

Certification and Labeling:

- **Organic Certification:** The production of fruits using sustainable and eco-friendly methods is ensured by meeting the requirements for organic certification.
- **Fair Trade Certification:** Fair trade procedures guarantee that farmers are fairly compensated, fostering both environmental and social sustainability.

Research and Innovation:

- **Biotechnology:** Fruit production may become more sustainable as a result of research into biotechnological techniques like breeding for disease resistance or better nutritional value.
- **Precision Agriculture:** Precision agriculture is the application of technologies and principles to manage spatial and temporal variability

associated with all aspects of agricultural production for the purpose of improving crop performance and environmental quality (Pierce, 1999).

Biodiversity Conservation and Environmental Stewardship:

- **Biodiversity Conservation:** Maintaining natural habitats on farms and around them promotes biodiversity, bringing in pollinators and natural predators that improve fruit quality. Ecosystems that are rich in biodiversity support ecological harmony and encourage the growth of fruit that is healthier.
- **Environmental Stewardship:** Environmental impacts of farming, such as greenhouse gas emissions and water pollution, are reduced through sustainable agricultural techniques. This stewardship protects ecosystems and guarantees that fruits are grown in harmony with the environment.

Conclusion:

Sustainable agricultural practices are a multifaceted effort to improve fruit quality and nutritional value. These practices include organic farming, integrated pest management, precision agriculture, agroforestry, soil health, water management, biodiversity preservation, and environmental stewardship. Farmers may produce fruits of greater quality and nutritional value by adopting these techniques, and they can also help build a more robust and ecologically balanced agricultural system. The present imperatives of food security, human health, and environmental sustainability are in line with this comprehensive approach to fruit production.

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Impact of Climate Change on Fruit Production

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Introduction

Climate change has become one of the most important environmental issues of the 21st century, affecting many sectors including agriculture and food security. Changes in climatic conditions such as rising temperatures, irregular rainfall patterns, and the increasing occurrence of droughts and floods have a direct impact on agricultural production. Fruit crops are particularly sensitive to these changes because they require specific environmental conditions, including suitable temperature, adequate moisture, and proper seasonal cycles for healthy growth, flowering, fruit set, and development.

When climate conditions change, the natural growth cycle of fruit crops can be disturbed. This may lead to problems such as irregular flowering, reduced pollination, and a higher incidence of pests and diseases. Higher temperatures can also reduce the chilling requirements needed for proper flowering in some fruit crops, which may result in poor fruit set and lower yields. Unpredictable rainfall may cause drought stress or waterlogging, both of which negatively affect plant growth and fruit quality. Therefore, climate change presents serious challenges for maintaining stable and sustainable fruit production.

Impact of Climate Change on Fruit Production

1. Rising Temperature and Its Effects

One of the most significant impacts of climate change on fruit production is the rise in global temperatures. Fruit crops are highly sensitive to temperature variations, and even slight increases in temperature can affect their growth, flowering, fruit development, and overall productivity.

Many temperate fruit crops such as apples, peaches, pears, and cherries require a certain number of chilling hours during winter to break dormancy. Chilling hours refer to the cumulative time when temperatures remain between 0°C and 7°C. When winters become warmer due to climate change, these chilling requirements may not be met, resulting in irregular flowering, poor fruit set, and reduced yields. Farmers in many regions are already experiencing delayed or uneven blooming in orchards.

High temperatures during the fruit development stage can also negatively affect fruit quality. Heat stress may cause sunburn on fruits, reduced fruit size, poor color development, and faster ripening. Rapid ripening shortens the shelf life of fruits and reduces their market value. For example, grapes and citrus fruits exposed to excessive heat may lose their flavor and sugar balance.

Extreme heat waves can damage fruit trees by increasing water loss through transpiration, causing dehydration and physiological stress. This stress can weaken plants, making them more susceptible to diseases and pests.

2. Changes in Rainfall Patterns

Climate change has significantly altered rainfall patterns around the world. Some regions experience prolonged droughts, while others face intense rainfall and flooding. These irregular precipitation patterns directly influence fruit production.

Drought conditions reduce soil moisture, limiting the availability of water for fruit trees. Water stress during critical growth stages such as flowering and fruit setting can cause flower drop, fruit abortion, and reduced yield. Fruit trees suffering from drought stress often produce smaller fruits with lower quality.

On the other hand, excessive rainfall can also be harmful. Waterlogged soils reduce oxygen availability to roots, leading to root rot and poor plant growth. Heavy rainfall during fruit maturation can cause fruit cracking, particularly in crops like cherries, pomegranates, and grapes. Moreover, humid conditions promote fungal diseases such as powdery mildew, anthracnose, and fruit rot.

Unpredictable rainfall also makes irrigation management difficult for farmers. Traditional farming calendars based on seasonal rainfall patterns are becoming unreliable, forcing farmers to adjust their cultivation practices.

3. Increased Incidence of Pests and Diseases

Climate change creates favorable conditions for many pests and plant pathogens. Warmer temperatures and higher humidity levels allow insects and diseases to spread more rapidly and survive in regions where they were previously absent.

Insects such as fruit flies, aphids, mites, and borers may reproduce more quickly in warmer climates. This leads to higher pest populations that can severely damage fruit crops. Fruit flies, for instance, can infest mango, guava, and citrus fruits, causing significant yield losses.

Similarly, fungal and bacterial diseases become more prevalent under changing climatic conditions. High humidity and temperature fluctuations promote the growth of pathogens responsible for diseases such as apple scab, citrus canker, and grape downy mildew. These diseases not only reduce fruit yield but also affect fruit quality and marketability.

The increased presence of pests and diseases often forces farmers to use more chemical pesticides, which raises production costs and may have negative environmental and health consequences.

4. Impact on Pollination

Pollination is a critical process for fruit production. Many fruit crops depend on pollinators such as bees, butterflies, and other insects for successful fertilization. Climate change can disrupt the relationship between flowering plants and their pollinators.

Changes in temperature and seasonal patterns may cause fruit trees to flower earlier or later than usual. If pollinators do not adjust their activity cycles accordingly, flowers may not be adequately pollinated. This mismatch between flowering time and pollinator activity can significantly reduce fruit set and yield.

Extreme weather events such as storms, heavy rainfall, and heat waves can reduce pollinator populations. The decline in pollinators is already a major concern in many parts of the world and poses a serious threat to fruit production.

5. Shift in Suitable Growing Regions

Climate change is gradually altering the geographical distribution of fruit crops. Regions that were once ideal for certain fruit species may become unsuitable due to rising temperatures or changing rainfall patterns.

For example, apple cultivation traditionally requires cool climates and sufficient winter chilling. As temperatures increase, lower altitude areas may no longer meet the chilling requirements for apple production. As a result, apple cultivation is shifting to higher altitudes or cooler regions. Tropical fruit crops such as mango and banana may expand into new regions where temperatures become warmer. While this shift may create opportunities in some areas, it also presents challenges for farmers who must adapt to new crops, soil conditions, and market demands.

6. Extreme Weather Events

Climate change has increased the frequency and intensity of extreme weather events such as storms, floods, droughts, and heat waves. These events can cause severe damage to fruit orchards.

Strong winds and storms can break branches, uproot trees, and cause premature fruit drop. Flooding can damage root systems and spread soil-borne diseases. Droughts can weaken trees and reduce their productivity for several years.

Hailstorms are particularly damaging to fruit crops because they can bruise fruits, making them unsuitable for sale. Extreme weather events not only reduce current yields but can also affect the long-term health of orchards.

7. Socio-Economic Implications

The socio-economic consequences of climate change on fruit production are profound. Farmers face declining incomes due to reduced yields and higher costs of adaptation. Traditional fruit-growing regions are experiencing shifts in cultivation zones, disrupting community livelihoods. For example, apple orchards in lower altitudes of Himachal Pradesh are being abandoned, while new orchards are being established at higher elevations. Such changes affect marketing, distribution, and trade networks. On a global scale, reduced fruit production leads to price volatility and decreased availability, impacting consumer nutrition. Fruits are essential sources of vitamins and antioxidants, and their scarcity poses risks to public health.

Strategies to Mitigate the Impact of Climate Change

- To sustain fruit production under changing climatic conditions, several adaptation and mitigation strategies must be adopted.
- One important strategy is the development of climate-resilient fruit varieties that can tolerate higher temperatures, drought, and diseases. Agricultural research institutions are working on breeding improved varieties of fruits such as mango, apple, and citrus.
- Improved water management practices such as drip irrigation, rainwater harvesting, and mulching can help conserve water and reduce drought stress in orchards. These techniques also improve water use efficiency.
- Another important approach is integrated pest management (IPM), which combines biological control, cultural practices, and limited pesticide use to manage pests and diseases in an environmentally friendly manner.
- Agroforestry practices, where fruit trees are grown alongside other crops and trees, can also help create a more stable microclimate and improve soil fertility. Additionally, the use of protective structures such as shade nets and windbreaks can reduce damage from extreme weather.

Conclusion

Climate change poses a serious threat to fruit production worldwide. Rising temperatures, irregular rainfall, increased pest and disease outbreaks, and extreme weather events are already affecting fruit yields and quality. Since fruit crops are highly sensitive to environmental conditions, even small climatic changes can have significant impacts on orchard productivity. However, with proper adaptation strategies, scientific research, and sustainable farming practices, it is possible to reduce the negative effects of climate change on fruit production. Developing climate-resilient varieties, improving water management, protecting pollinators, and adopting integrated pest management are some of the key measures that can help farmers cope with changing climatic conditions. Ensuring sustainable fruit production is essential not only for the livelihoods of farmers but also for global food security and human nutrition. Therefore, coordinated efforts from governments, researchers, and farmers are necessary to address the challenges posed by climate change and safeguard the future of fruit cultivation.

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Sustainable Cultivation Practices in Mango Orchards

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Introduction

Mango (*Mangifera indica*), often called the "king of fruits," holds immense economic, cultural, and nutritional value, especially in tropical and subtropical regions. However, conventional mango cultivation methods often rely heavily on chemical inputs, excessive water use, and practices that degrade soil health. In the face of climate change, resource depletion, and environmental concerns, sustainable cultivation practices have become essential for long-term productivity and ecological balance.

Sustainable mango farming focuses on maintaining soil fertility, conserving water, reducing chemical dependency, and enhancing biodiversity while ensuring profitable yields for farmers.

Site Selection and Orchard Planning

Sustainability begins with proper site selection and orchard design.

- **Climate and Soil Requirements:** Mango thrives in well-drained loamy soils with a pH range of 5.5 to 7.5. Avoid waterlogged areas, as mango roots are sensitive to excess moisture. Selecting land with good sunlight exposure and natural wind protection reduces the need for artificial interventions.
- **Spacing and Layout:** High-density planting systems can be adopted for efficient land use, but spacing must ensure adequate sunlight penetration and air circulation. Proper spacing reduces pest and disease incidence naturally.
- **Windbreaks and Buffer Zones:** Planting trees like neem, silver oak etc, around orchards acts as windbreaks, reducing soil erosion and protecting mango trees. Buffer zones also support biodiversity by providing habitats for beneficial organisms.

Soil Health Management

Healthy soil is the foundation of sustainable mango production.

- **Organic Matter Addition**: Incorporating farmyard manure, compost, and green manure improves soil structure, water retention, and microbial activity. Organic amendments also enhance nutrient availability over time.
- **Cover Cropping**: Growing legumes or grasses between mango rows prevents soil erosion, suppresses weeds, and enriches soil nitrogen levels. Cover crops also improve soil biodiversity.
- **Mulching**: Applying organic mulch (such as straw, leaves, or coconut husk) conserves soil moisture, regulates temperature, and reduces weed growth. Mulching also adds nutrients as it decomposes.
- **Reduced Tillage**: Minimizing soil disturbance helps maintain soil structure and microbial life, reducing erosion and improving long-term fertility.

Water Management

Efficient water use is crucial for sustainable mango cultivation.

- **Drip Irrigation**: Drip irrigation delivers water directly to the root zone, minimizing wastage and evaporation. It can reduce water usage by up to 50% compared to traditional methods.
- **Rainwater Harvesting**: Constructing farm ponds or harvesting rainwater ensures water availability during dry periods and reduces dependence on groundwater.
- **Irrigation Scheduling**: Water should be applied based on plant growth stages. For example, flowering and fruit development stages require careful irrigation, while excessive watering during maturity can reduce fruit quality.

Nutrient Management

Balanced nutrition is key to sustainable productivity.

- **Integrated Nutrient Management (INM):** Combining organic manures with biofertilizers and minimal chemical fertilizers ensures a steady nutrient supply while maintaining soil health.
- **Biofertilizers:** Microorganisms such as nitrogen-fixing bacteria and phosphate-solubilizing bacteria enhance nutrient availability naturally.
- **Leaf and Soil Testing:** Regular testing helps farmers apply only the required nutrients, avoiding overuse and reducing environmental pollution.

Pest and Disease Management

Sustainable pest control focuses on ecological balance rather than chemical dependence.

1. **Integrated Pest Management (IPM):** IPM combines biological, cultural, mechanical, and minimal chemical methods to manage pests effectively.
    - **Biological control:** Use of natural predators like ladybird beetles
    - **Botanical pesticides:** Neem-based sprays
    - **Cultural practices:** Proper pruning and sanitation
2. **Disease Prevention:** Maintaining proper spacing, removing infected plant parts, and improving air circulation reduces fungal and bacterial diseases.
3. **Use of Resistant Varieties:** Planting disease-resistant mango varieties minimizes the need for chemical treatments.

Training and Pruning

It plays a crucial role in sustainable mango farming.

- Improves sunlight penetration
- Enhances air circulation
- Reduces pest and disease incidence
- Facilitates easier harvesting

Biodiversity and Agroforestry

Promoting biodiversity enhances orchard sustainability.

- **Intercropping:** Growing crops like legumes, vegetables, or medicinal plants between mango trees provides additional income and improves soil fertility.
- **Agroforestry Systems:** Integrating mango with other tree species creates a balanced ecosystem, improves carbon sequestration, and enhances resilience to climate stress.
- **Pollinator Conservation:** Encouraging bees and other pollinators improves fruit set and yield. Avoiding harmful pesticides helps protect these beneficial organisms.

Climate-Resilient Practices

Climate change poses significant challenges to mango cultivation.

- **Drought Management:** Mulching, drip irrigation, and drought-tolerant rootstocks help orchards withstand water scarcity.

- **Heat Stress Mitigation:** Shade management and proper irrigation reduce heat damage to flowers and fruits.
- **Carbon Sequestration:** Mango orchards act as carbon sinks. Sustainable practices like organic farming and agroforestry increase carbon storage and reduce greenhouse gas emissions.

Harvesting and Post-Harvest Management

Sustainable practices extend beyond cultivation.

- **Proper Harvesting Techniques:** Fruits should be harvested at the correct maturity stage to ensure quality and reduce losses.
- **Post-Harvest Handling:** Using eco-friendly packaging, minimizing chemical treatments, and maintaining proper storage conditions reduce waste and environmental impact.
- **Value Addition:** Processing mango into products like pulp, juice, or dried slices increases profitability and reduces post-harvest losses.

Economic and Social Benefits

Sustainable mango cultivation offers multiple advantages:

- Reduced input costs over time
- Improved soil fertility and long-term productivity
- Better market value for organic produce
- Enhanced farmer resilience to climate change
- Improved health for farmers and consumers

Conclusion

Sustainable cultivation practices in mango orchards are essential for balancing productivity with environmental conservation. By adopting methods such as organic soil management, efficient water use, integrated pest management, and biodiversity enhancement, farmers can ensure long-term profitability and ecological stability.

As global demand for sustainably produced fruits continues to rise, transitioning to eco-friendly mango cultivation is not just an environmental necessity but also an economic opportunity. Sustainable mango orchards represent a harmonious blend of tradition, innovation, and responsibility toward future generations.

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Scientific Cultivation of Rainy Season Okra: A Complete Guide for Higher Yield and Better Profitability

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Introduction

Okra (Abelmoschus esculentus L.), popularly known as lady's finger or bhindi, is one of the most important vegetable crops cultivated in tropical and subtropical regions of the world. It is widely appreciated for its tender green pods, nutritional value, and adaptability to different agro-climatic conditions. India is the largest producer of okra, contributing significantly to global production. Due to its short duration, continuous harvesting, and high market demand, okra provides an excellent source of income for vegetable growers.

Rainy season (Kharif) cultivation of okra is particularly profitable because market demand remains high during this period. However, excessive rainfall, waterlogging, high humidity, and severe pest and disease infestations often reduce productivity. Scientific cultivation practices, including the use of improved varieties, balanced nutrient management, efficient drainage, and integrated pest management, are essential for achieving higher yields and superior quality fruits.

Importance of Okra

Okra is not only a popular vegetable but also a valuable nutritional crop. Tender fruits contain carbohydrates, proteins, dietary fibre, vitamins A, B-complex and C, calcium, phosphorus, potassium, magnesium, and iron. The mucilage present in okra fruits is beneficial for digestion and has several medicinal properties. Due to increasing consumer awareness regarding healthy diets, the demand for fresh okra continues to rise in both domestic and export markets.

Climate Requirements

Okra is a warm-season crop that grows best under tropical and subtropical climatic conditions. The optimum temperature for seed germination ranges from 25–30°C, while 25–35°C is considered ideal for vegetative growth and fruit development. During the rainy season, moderate rainfall combined with adequate sunshine promotes vigorous growth. However, prolonged waterlogging adversely affects root development and increases disease incidence.

Excessive humidity also encourages fungal diseases and insect pests. Therefore, efficient drainage is one of the most important components of successful rainy season cultivation.

Suitable Soil

Okra can be cultivated in a wide variety of soils ranging from sandy loam to clay loam. However, fertile, well-drained sandy loam soils rich in organic matter are considered ideal. The optimum soil pH ranges from 6.0 to 7.5. Fields with poor drainage should be avoided during the rainy season because standing water causes root rot, nutrient loss, and poor crop establishment.

Improved Varieties

Selection of suitable varieties is the first step towards successful cultivation. Farmers should prefer varieties resistant to Yellow Vein Mosaic Virus and other important diseases.

Some popular varieties include:

Arka Anamika, Arka Abhay, Parbhani Kranti, Pusa A-4, Kashi Pragati Kashi Kranti, Punjab Padmini, VRO-6, VRO-22

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Land Preparation

The land should be ploughed two to three times followed by harrowing to obtain a fine tilth. Well-decomposed Farmyard Manure (FYM) at 20–25 tonnes per hectare should be incorporated during the final ploughing. Raised beds or ridge-and-furrow systems are highly recommended during the rainy season because they facilitate rapid drainage and improve root aeration. Fields should be levelled properly before sowing.

Seed Rate and Seed Treatment

A seed rate of 8–10 kg per hectare is generally sufficient for rainy season cultivation. Before sowing, seeds should be treated with suitable fungicides or biological agents to protect seedlings from soil-borne diseases.

Biofertilizer inoculation with Azotobacter or Azospirillum improves nitrogen fixation and enhances plant growth.

Time of Sowing

The ideal sowing period varies with climatic conditions. In North India, sowing is generally carried out from June to July, immediately after the onset of monsoon.

Timely sowing ensures better germination and reduces crop losses caused by heavy rainfall.

Spacing

Proper spacing facilitates aeration, sunlight penetration, and intercultural operations.

Recommended spacing: Row to row: 45–60 cm, Plant to plant: 20–30 cm Seeds should be sown at a depth of about 2–3 cm.

Nutrient Management

Balanced fertilization is essential for obtaining high yields and superior fruit quality.

Organic Manure Apply 20–25 tonnes FYM per hectare before sowing.

Organic manure improves soil structure, microbial activity, moisture retention, and nutrient availability.

Chemical Fertilizers

Recommended fertilizer dose: - Nitrogen (N): 100–120 kg/ha

- Phosphorus (P_2O_5): 50–60 kg/ha

- Potassium (K_2O): 50–60 kg/ha

Apply the entire phosphorus and potash along with half the nitrogen as basal application. The remaining nitrogen should be applied in two equal split doses at 25–30 days and 45–50 days after sowing.

Micronutrients

Foliar spray of zinc, boron, calcium, and magnesium improves flowering, fruit set, and fruit quality. Application of seaweed extract or amino acid formulations also enhances crop growth under stress conditions.

Irrigation and Drainage

Although rainfall usually satisfies crop water requirements during the rainy season, proper drainage remains extremely important. Waterlogging for even 24–48 hours may damage the root system and reduce yield significantly.

Supplemental irrigation should be provided only during prolonged dry spells. Drip irrigation combined with plastic mulch is highly effective in improving water-use efficiency.

Weed Management

Weeds compete with the crop for nutrients, moisture, sunlight, and space. The crop should remain weed-free during the first 30–40 days after sowing. Two manual weedings at approximately 20 and 40 days after sowing are generally sufficient. Mulching helps suppress weed growth, conserve soil moisture, and reduce soil erosion during heavy rainfall. Integrated weed management provides the best long-term results.

ISSN: 3049-2289

Integrated Pest Management

Rainy season cultivation is frequently affected by several insect pests.

Major pests include: Fruit and shoot borer, Jassids, Aphids, Whiteflies, Red spider mites

Integrated Pest Management (IPM) practices include:

- Use of yellow sticky traps for whiteflies and aphids.
- Installation of pheromone traps for fruit borers.
- Regular field monitoring.
- Removal of damaged shoots and fruits.
- Conservation of beneficial insects.
- Need-based application of recommended insecticides following label instructions.
- Avoiding unnecessary pesticide applications to reduce resistance development.

Disease Management

High humidity during the rainy season favours several fungal and viral diseases.

Important diseases include: Yellow Vein Mosaic Virus (YVMV)

This is one of the most destructive diseases of okra.

Symptoms include yellow veins, reduced fruit size, and poor yield.

Management:

- Use resistant varieties.
- Control whiteflies.
- Remove infected plants immediately.

Powdery Mildew- White powdery growth appears on leaves, reducing photosynthesis.

Maintain proper field sanitation and apply recommended fungicides whenever necessary.

Intercultural Operations

Earthing-up should be carried out approximately one month after sowing to strengthen plants and improve drainage.

Timely removal of diseased plants and damaged fruits reduces pest and disease spread.

Regular field inspection enables early identification of crop problems.

Harvesting

Tender fruits become ready for harvesting about 45–55 days after sowing.

Harvesting should be carried out every 2–3 days because delayed harvesting results in fibrous and unmarketable fruits.

Harvesting during early morning hours improves freshness and shelf life.

Care should be taken to avoid damaging the plants during harvesting.

Post-Harvest Handling

Harvested fruits should be graded according to size and quality. Damaged or diseased fruits should be discarded.

Clean plastic crates are preferred for transportation because they minimize mechanical injury.

Proper packaging and rapid transportation to markets help farmers obtain better prices.

Expected Yield

Scientific cultivation practices considerably improve productivity.

Expected yields are: - Open-pollinated varieties: 12–18 tonnes per hectare and for Hybrid varieties: 18–25 tonnes per hectare

Under excellent crop management and favourable environmental conditions, even higher yields may be achieved.

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