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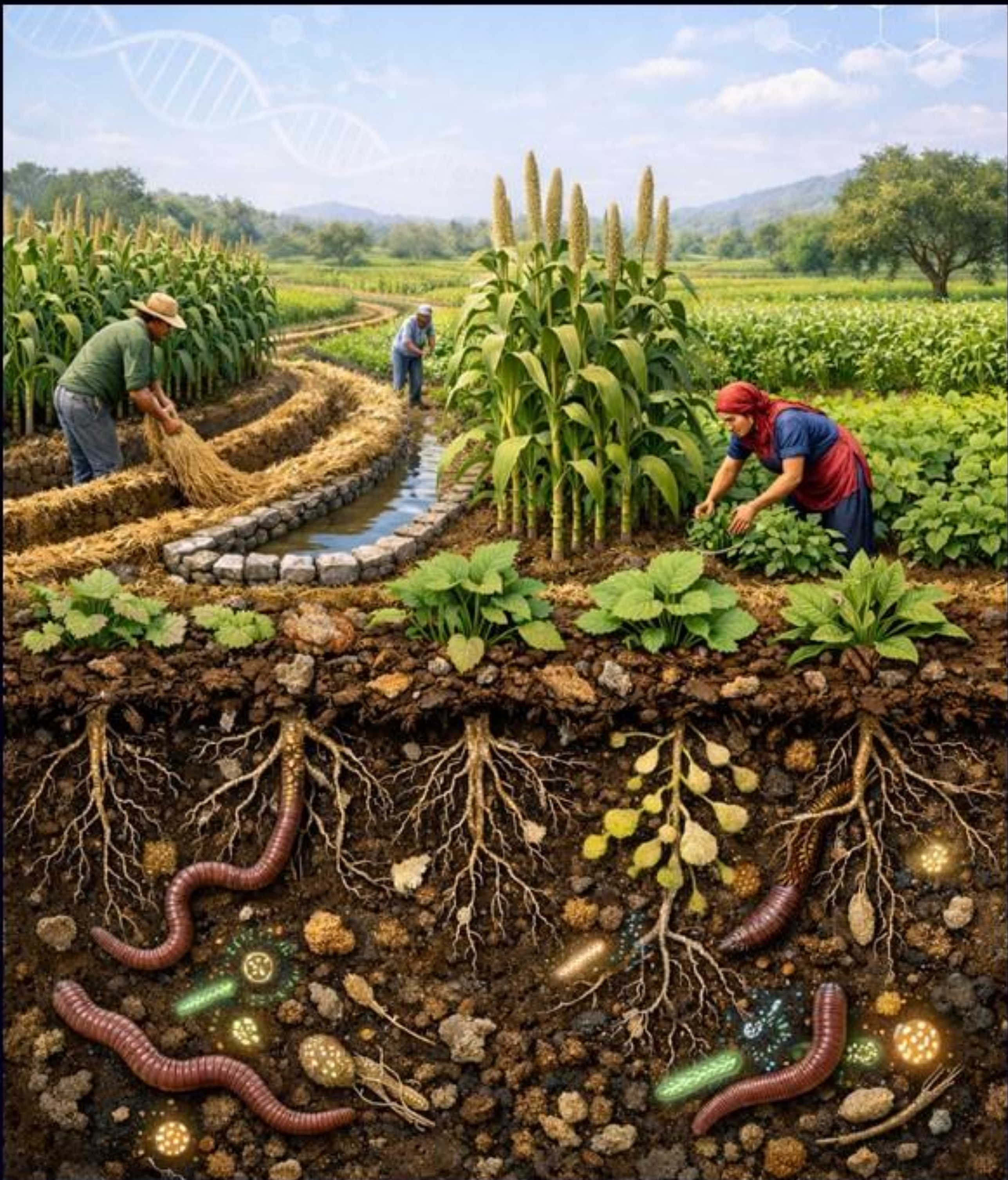

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PREPARATION OF MATKA KHAD, EGG AMINO ACID AND FISH AMINO ACID IN ORGANIC FARMING

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ABSTRACT

Organic farming emphasizes the use of natural inputs to maintain soil fertility, promote plant health, and ensure environmental sustainability. Among the various bio-formulations used by farmers, Matka Khad, Egg Amino Acid (EAA), and Fish Amino Acid (FAA) have gained prominence as simple, cost-effective, and highly beneficial organic nutrient sources. These preparations supply essential nutrients, stimulate microbial activity in the soil, and enhance crop growth and yield without relying on synthetic fertilizers. This article discusses the easy and farmer-friendly methods of preparing these formulations, their nutrient composition, and their role in strengthening the organic farming ecosystem.

KEYWORDS: Amino acid bio-fertilizers, indigenous liquid manures, matka Khad, organic farming, sustainable nutrient management

INTRODUCTION

Organic farming aims to create a self-sustaining and eco-balanced production system where soil, plants, animals, and microorganisms coexist harmoniously. To achieve this, farmers are increasingly adopting homemade organic nutrient solutions that can be prepared from locally available materials. *Matka Khad*, Egg Amino Acid, and Fish Amino Acid are three such vital inputs that enrich the soil with organic carbon and biologically available nutrients.

- **Matka Khad**, a traditional fermented liquid manure, is prepared using cow dung, cow urine, jaggery, and pulses flour, and is rich in beneficial microbes and nutrients. (Chadha *et al.*, 2012)
- **Egg Amino Acid** serves as a rich source of nitrogen, amino acids, and micronutrients that enhance vegetative growth and vigor.
- **Fish Amino Acid**, made by fermenting fish waste with jaggery, provides proteins, enzymes, and growth hormones beneficial for flowering and fruiting stages.

These formulations not only promote plant health but also minimize dependence on costly chemical fertilizers, thereby supporting sustainable, low-input organic farming. Their simplicity of preparation and effectiveness make them popular among small and marginal farmers, aligning perfectly with the goals of natural farming movements also across India.

MATKA KHAD (MUD POT MANURE)

The term comes from the fact that the *matka khad* is made in a mud pot, or *matka*.

Ingredients for the preparation of *Matka khad*

1. Chickpea flour : 1 kg
2. Jaggery : 1 kg
3. Fresh indigenous cow dung (not older than 24 hours) : 15 kg
4. Indigenous cow urine : 15 L
5. One handful soil from below the tree of *peepal* (*Ficus religiosa*) or banyan or neem or forest or bund of the field,

Preparation

All the required ingredients were thoroughly combined in a mud pot by adding 15 litres of water to ensure uniform mixing. The prepared mixture was allowed to undergo a natural fermentation process for a period of 15 days, during which it was stirred once daily for approximately five minutes in a clockwise direction using a wooden stick. Regular stirring facilitated proper aeration and enhanced microbial activity, thereby promoting effective decomposition and nutrient solubilization. At the end of the 15-day fermentation period, the organic manure attained a stable and usable form. The fermented mixture was then carefully filtered using a clean cotton cloth to remove coarse and undissolved materials, resulting in a clear liquid extract. This filtered liquid obtained from one mud pot was subsequently diluted with 200 litres of clean water to achieve the desired concentration. The diluted solution was applied as a foliar spray, which was sufficient to cover one acre of crop area, ensuring uniform nutrient distribution and effective utilization by the plants.

Usage:

1. It can be used as drenching in wider spaced crops.
2. The *matka khad* filled in a can with a tape, is kept at one side of the irrigation channel and the *matka khad* come out drop by drop from the can in the irrigation channel and reaches entire field with the irrigation water. About 400 litres of *matka khad* is sufficient for direct use with irrigation water or by drip irrigation.
3. The spraying of this liquid manure is done every 15 days interval up to the 50% flowering stage.

Egg amino acid

Eggs, lemon and jaggery are used to make egg amino acids. It is a blend of nutrients that encourages fruit set, flowering, and plant growth. It aids in the treatment of crop calcium deficiencies. Egg amino acids are now a lucrative and cutting-edge bio-based product that has greatly advanced organic farming practices. This natural and biodegradable solution, which is made from eggs, is a powerful organic fertilizer and plant growth stimulant since it contains a wide variety of important amino acids. Egg amino acids have emerged as a crucial element in the quest for high-yielding and environmentally conscious farming methods due to their capacity to increase soil fertility, boost crop output, and strengthen plant resilience to stresses.

Ingredients for the preparation of egg amino acid (20L) (Shiyas, 2023)

1. Eggs : 15 No.
2. Lemon : 25 kg
3. Jaggery : 3 g

Preparation:

For the preparation of this formulation, fresh eggs are placed in an airtight container, after which freshly extracted lemon juice is poured in sufficient quantity to ensure that the eggs are completely immersed. The container is then tightly sealed and stored undisturbed. Over a period of 15 days, the acidic lemon juice gradually dissolves the eggs, resulting in a homogeneous solution. After this dissolution stage, the mixture is stirred thoroughly, and an equal quantity of cooled molten jaggery is added to enhance nutrient availability and fermentation. The container is again sealed and allowed to ferment further. After 30 days from the initial preparation, the mixture is filtered using a clean cotton cloth to remove any residues or impurities. The resulting filtrate is a well-processed liquid formulation, suitable for field application. This method ensures effective extraction of nutrients from the eggs and their stabilization through fermentation, making the final product ready for agricultural use.

Usage:

- 4 mL egg amino acid diluted in 1L water can be used as basal application or foliar spray.

FISH AMINO ACID

It is composed of jaggery and fish. It encourages plant development and has a high nitrogen content. Additionally, it possesses insect-repelling qualities. There are several noteworthy advantages to this creative farming technique. In order to create a loose soil structure that supports the flourishing biomass of microorganisms and earthworms and ensures a healthy and sustainable soil environment, it first concentrates on improving soil fertility and enriching nutrients. Second, it actively encourages the growth of crop roots and leaves, which improves photosynthesis and the development of the crop as a whole. With an anticipated 10% to 40% increase in production, the effect on farmers' productivity is as remarkable. Additionally, the technique improves crop quality by extending the harvest season and enhancing long-term storage capacity without sacrificing nutritional content or freshness. Additionally, the treatment increases crops' ability to tolerate pests and illnesses by strengthening their resilience to a variety of obstacles. For specific insect difficulties, it can also function as an effective repellent against rice bug and pod bugs when sprayed at a recommended dilution rate of 15-20 mL per liter of water. All things considered, this all-encompassing strategy enables farmers to produce better crops, promote sustainable agriculture, and satisfy the needs of an expanding population. (Maghirang, 2011)

Ingredients for the preparation of fish amino acid (30L)

1. Fish : 30 kg
2. Jaggery : 30 kg

Preparation:

Egg amino acid is prepared using fish materials, which may include any part of the fish such as the head, bones, and internal organs, making the process both economical and sustainable. The fish components are cut into small pieces and placed in a large container in layers, with each layer consisting of approximately one kilogram of fish. After placing each fish layer, an equal layer of finely shredded jaggery is added to facilitate fermentation and extraction of nutrients. This layering process is repeated systematically, ensuring slight spacing between layers to allow proper microbial activity. Once all the layers are arranged, the container is sealed in an airtight manner to create anaerobic conditions essential for fermentation. The mixture is then left undisturbed for a period of about 30 days, during which enzymatic and microbial processes break down the fish tissues and release amino acids into the solution. After the fermentation period, the container is opened and the contents are sieved to remove solid residues. The filtered liquid obtained is the final egg amino acid preparation, which is then ready for agricultural use.

Usage:

- 4mL fish amino acid diluted in 1 L of water can be used for a basal application or as a foliar spray.
- Fish amino acid fertilisers have an NPK ratio of 4:1:1. High in nitrogen (N) and low in phosphorus (P) and potassium (K). It also contains trace elements and secondary nutrient elements like calcium and magnesium.

CONCLUSION

The use of *Matka Khad*, *Egg Amino Acid*, and *Fish Amino Acid* represents a practical and sustainable approach to nutrient management in organic farming. These indigenous formulations recycle farm and household wastes into valuable bio-fertilisers, enhancing soil fertility, plant growth, and resistance to pests and diseases. By integrating these preparations into regular farm practices, farmers can reduce input costs, improve crop quality, and contribute to the long-term health of agro-ecosystems. Encouraging the preparation and application of such natural concoctions at the farm level is a vital step toward achieving resilient, chemical-free, and environmentally responsible agriculture.

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ENHANCING LAND PRODUCTIVITY OF TRIBAL FARMERS THROUGH SOIL AND WATER CONSERVATION INTERVENTIONS: A SUCCESS STORY OF COMMUNITY PARTICIPATION

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ABSTRACT

Tribal farmers of Boothanatham village in the Nilgiris face persistent challenges of low agricultural productivity due to rainfed farming, limited access to technologies, weak institutional linkages, and inefficient water use. Under the Tribal Sub-Plan, ICAR–Indian Institute of Soil and Water Conservation implemented participatory soil and water conservation interventions integrating lift irrigation, solar and diesel pumps, micro-irrigation, farm ponds, crop diversification, and capacity building. These interventions enabled assured irrigation, adoption of improved technologies, cultivation of high-value crops, and strengthened institutional linkages, resulting in enhanced land productivity, increased farm income, and improved livelihood security through strong community participation.

KEYWORDS: Community participation, land productivity, lift irrigation, soil and water conservation tribal sub-plan

INTRODUCTION

Tribal communities serve as authentic representations of a nation's cultural heritage and are considered the indigenous population. In India, they constitute an integral part of our human resource base, possessing rich indigenous knowledge and skills across all sectors, including agriculture. The Nilgiris, a biodiversity-rich part of the Western Ghats is exceptional for its diverse ecosystem features like various types of forests, grasslands, agricultural lands, and wetlands. It has five of the ancient tribal communities namely Todas, Kotas, Irulas, Kurumbas, and Paniyas. The tribes of this region depended on the forest for their livelihood. During the 19th century, the forest land use was converted into tea, coffee plantations and other commercial crop cultivation by the Britishers. The trend of forest land use conversion has continued, depriving tribal people of access to forest resources, such as medicinal plants, honey, and fuelwood. As a result, many tribal families were forced to migrate from their native lands, work as underpaid labourers and endure a decline in their socio-economic condition. To address these challenges, the Government of India launched the Tribal Sub-Plan (TSP) with the aim of improving the socio-economic status of tribal communities through various developmental initiatives.

ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Udhagamandalam, also shoulders the responsibility of uplifting the tribal community through supporting agricultural and other livelihood activities through TSP. The tribal village of Boothanatham, Udhagamandalam Taluk, The Nilgiris has been selected for the implementation of TSP, located in the middle of a dense forest (Nilgiri Biosphere Reserve) on the border between Tamil Nadu and Karnataka. This village is predominantly inhabited by Irula tribes. The major area of the region is covered by dense forest, and a meagre portion of land is utilized for agriculture. The Irulas tribes are indigenously lives inside the forest reserve and their livelihood security is depends on forest resources. But the constitution of National Park and wild life protection acts made illegal the traditional occupation of the Irulas tribes and their livelihood security is in question. However, Recently, Irulas families have been granted sizable land for cultivation under forest rights act 2006. Even though the area receives normal rainfall of 1000 mm and a tributary perennial river is aside of the land allotted, the tribal farmers could not get desired yield.

SURVEY AND PROBLEM IDENTIFICATION

The developmental initiatives aimed at improving the socio-economic status of the tribal community will be successful only if they are implemented in accordance with local needs. Hence, a preliminary survey on participatory mode was conducted by the scientists of ICAR-IISWC, RC, Udhagamandalam, for the need analysis through interaction with the local people. Together with the village head and the landless and land holders, we traversed the entire village and documented the available resources.

Survey and interaction with village people

The perennial river running near the agricultural fields

PROBLEMS IDENTIFIED

Based on the survey and interactions with the local communities, we identified some problems contributing to the prevailing socio-economic conditions of the people. The issues are classified into 5 major categories.

1. LOW PRODUCTIVITY IN RAINFED AGRICULTURE

The farmers cultivate crops such as small millets, groundnut and pulses under rainfed conditions. The crop productivity was very low in the rainfed condition compared to the nearby farmers cultivating the same crops under irrigated conditions. Due to rainfed farming, farmers cultivate only one crop during the south west monsoon, remaining period the field is left as fallow. Lack of irrigation facilities restricted the choice of crops that can be cultivated in this region. As the farmers predominantly grow the local crop varieties, attention given for the nutrient management is rare. The farmers are habitual to apply Farm Yard Manure (FYM) before the cropping season and incorporate in the soil, which is the primary source of nutrients. The application of nutrients from inorganic sources is rarely practiced by the farmers. Due to the above facts, the productivity was very less in the region.

2. LACK OF CROP DIVERSIFICATION

Farmers mostly rely on rainfed crops and cultivated the same in every season. This practice affects the soil fertility and also market opportunities. Crop diversification with commercial crops will improve the income of the farmers.

3. LIMITED ACCESS TO IMPROVED TECHNOLOGIES

The village is located in a remote and isolated area. Hence, the awareness and accessibility of new and improved technologies and varieties have not effectively reached the farmers.

4. WEAK SOCIAL AND INSTITUTIONAL LINKAGES

The village farmers have very limited contact with the government departments and banking institutions. The farmers does not have any formal association for initiating or taking part in collective agricultural activities.

5. INEFFICIENT UTILIZATION OF WATER RESOURCES

The Moyar, a perennial river, is one of the tributaries of the Bhavani River that flows through the village’s agricultural lands. Despite the year-round availability of ground water, the lack of electricity in the village poses a significant constraint on farmers’ to effectively utilize this water for crop cultivation. Farmers those who have financial capacity to rent diesel pumps irrigate their fields during critical crop growth stages. Others left the land fallow except the rainy season. Furthermore, the sloppy agricultural lands are poorly maintained without proper soil and water conservation measures.

IDENTIFIED PROBLEM VS. INTERVENTION IMPLEMENTED

Independent technologies on renewable energy utilization, soil and water conservation, crop production and value addition are available and in operations elsewhere. However, we integrated these energy and water technologies in vicinity of Irulas tribal Geo-entity for agricultural and social upliftment. Lift irrigation was introduced along with water saving micro irrigation techniques, like sprinklers, to improve water availability for both domestic and agricultural purpose. Initially, a 8 HP diesel pump was installed to lift water from the river, and sprinklers systems were provided to ensure irrigation for the crops. However, adopting solar energy for lift irrigation presents a sustainable, eco-friendly, and economically viable solution for enhancing agricultural productivity. Therefore, in addition to diesel pump a 5 HP solar pump was installed to lift water for irrigation purpose.

Diesel pump provided for lift irrigation


Solar pump setup for lift irrigation

This initiative encouraged the farmers to cultivate vegetable crops under assured irrigation. In addition to millets, crops like garlic, onion, pulses and beans are now grown using micro irrigation leading to enhanced productivity of the agricultural land. A farm pond was also constructed to harvest rainwater, which helps conserve water resources and ensures a reliable supply of irrigation during dry spells, particularly benefiting farmers cultivating crops through micro-irrigation. New varieties and cultivation technologies were introduced through government and non-governmental organizations enabling the farmers to adopt them.

Garlic crop with sprinkler irrigation

Since the farmers are not continuously engaged in agricultural activities, they do not possess their own sprayers and rent battery-operated sprayers at a rate of ₹30 per hour. Therefore, battery-operated sprayers were also provided to the farmers to facilitate timely and efficient pest and disease management operations. In addition to that small farm implements also distributed to the farmers for carrying out agricultural operations.

Several capacity building programmes were conducted focusing on soil and water conservation, integrated nutrient management, water harvesting technologies, and efficient utilization of water. During these training, experts and officials from various departments provided detailed guidance of government schemes and subsidies available to tribal farmers. This facilitated the collaboration between farmers and Horticultural department, Agricultural engineering department, and Forestry department resulting in increased adoption of technologies and improved livelihood opportunities.

The user groups and self-help groups have been formed and linked with Banks in near by town and necessary linkages have been created with line departments and research institutions for technological updates.

CONCLUSIONS

The tribal farmers of Boothanatham village have been able to increase their agricultural income by cultivation an additional crop with the help of lift irrigation systems that draw water from the tributary of river. This initiative has also helped them save on the rental costs previously spent on diesel pumps. With the help of pumps and the micro irrigation system, farmers are able to cultivate high value vegetable crops like beans, garlic etc. Moreover, the farmers also effectively use the sprayers for timely plant protection activities. Their knowledge and skills in adopting new improved technologies have been enhanced through various capacity building programmes. Additionally, the linkage between the village and other government departments has been strengthened, further supporting the enhanced agricultural production. The scheme launched by Government of India for Tribal farmers is highly beneficial in improving land productivity and livelihood security of tribal communities in Bothanatham village of the Nilgiris hill.

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KEY TRANSCRIPTION FACTOR FAMILIES IN ABIOTIC STRESS TOLERANCE

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ABSTRACT

Plants are often exposed to abiotic stresses such as drought, salinity, temperature extremes, and oxidative stress, which markedly impair growth and productivity. Being sessile, plants depend on complex molecular mechanisms for stress adaptation, with transcription factors (TFs) playing a pivotal role in regulating stress-responsive gene expression. Major TF families, including AP2/ERF, NAC, bZIP, MYB, WRKY, HSF, and bHLH, have been widely reported as key regulators of abiotic stress tolerance in crops and model plants. These TFs modulate processes such as osmotic adjustment, ROS scavenging, ion balance, and stress signaling via ABA-dependent and independent pathways.

KEYWORDS: ABA, abiotic stress tolerance transcription factors, stress-responsive gene

INTRODUCTION

Plants, being immobile, are constantly challenged by environmental stresses such as drought, salinity, extreme temperatures, and oxidative damage. These abiotic stresses strongly influence their growth, development, and yield. Since plants cannot move away from stress like animals, they have evolved complex molecular systems to adapt and survive. A key part of this adaptation is controlled by transcription factors (TFs)-proteins that attach to specific DNA sequences and regulate the activity of stress-related genes, working like switches to turn protective responses on or off.

In the last twenty years, researchers have discovered many important TF families that help plants tolerate stress, both in model species like Arabidopsis thaliana and in crops such as rice, wheat, and maize. Among these, the AP2/ERF (DREB/CBF), NAC, bZIP, MYB, WRKY, HSF, and bHLH families play especially crucial roles. These TFs are organized into stress-responsive pathways that can be broadly divided into ABA-dependent and ABA-independent mechanisms. This article highlights the major transcription factors, their functional pathways, and their applications in developing stress-resilient crops.

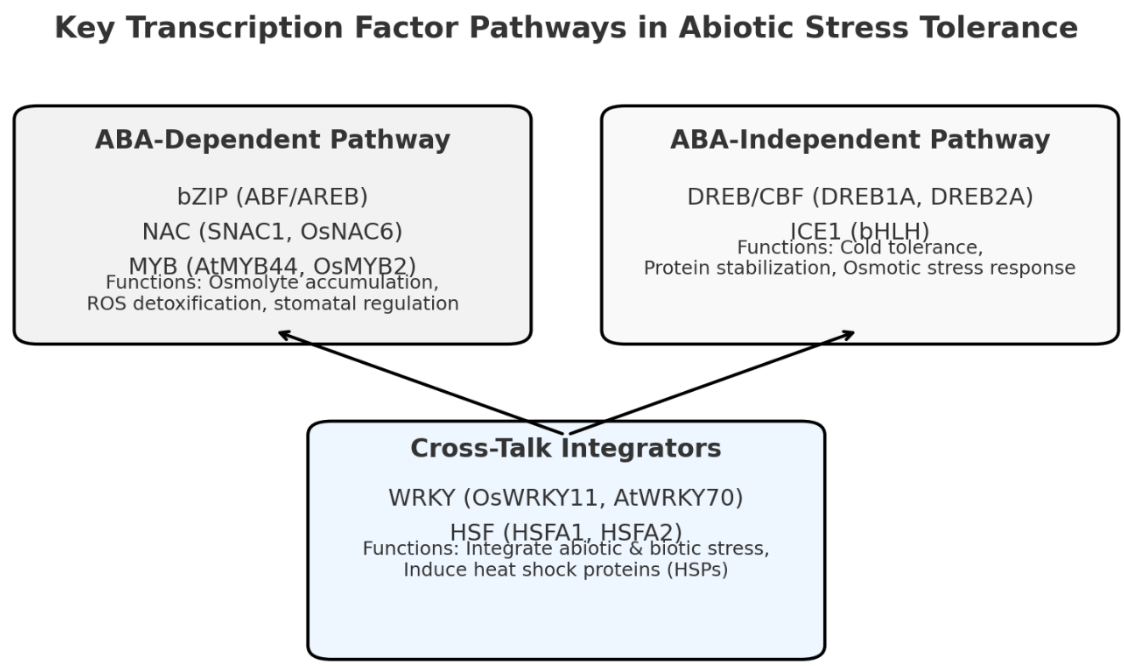

Fig: The schematic diagram showing how key transcription factors operate in ABA-dependent, ABA-independent, and cross-talk pathways for abiotic stress tolerance.

A BA-DEPENDENT PATHWAYS: GUARDIANS OF DROUGHT AND SALINITY

Abscisic acid (ABA) is a central hormone in plant stress signaling, especially under drought and salinity conditions. Transcription factors that respond to ABA play a crucial role in regulating water balance, osmolyte production, and the accumulation of protective proteins.

1. bZIP family (ABF/AREB factors): These TFs bind to ABA-responsive elements (ABREs) in promoter regions. For example, AREB1 and ABF3 in Arabidopsis regulate drought-inducible genes. In rice, OsbZIP23 plays a similar role, enhancing drought and salt tolerance.
2. NAC family: Many NAC proteins, such as SNAC1 and OsNAC6, respond to ABA accumulation. They modulate stomatal closure, ROS detoxification, and cuticle reinforcement.
3. MYB factors: Several MYBs, including AtMYB44 and OsMYB2, integrate ABA signaling with osmotic stress responses, contributing to drought adaptation.

Together, these TFs act as the first responders to water deficit by ensuring plants conserve water and maintain cellular homeostasis.

ABA-INDEPENDENT PATHWAYS: COLD AND OSMOTIC STRESS DEFENCES

1. Some transcription factors bypass ABA signaling, directly activating stress-protective genes.

2. DREB/CBF proteins: Perhaps the best studied, these TFs recognize dehydration-responsive elements (DRE/CRT) in promoters. DREB1/CBFs regulate cold-responsive genes (COR15A, RD29A) and are essential for freezing tolerance. DREB2 members respond to drought and heat stress by mediating the production of osmo-protectants and chaperones.
3. ICE1 (bHLH family): This TF activates CBF genes under cold stress, serving as a critical upstream regulator of the cold stress pathway.
4. These TFs represent the independent warriors of stress adaptation, functioning even when ABA levels remain low.

INTEGRATORS OF MULTIPLE SIGNALS

Some TFs do not strictly follow ABA-dependent or independent categories but instead act as crosstalk mediators.

1. **WRKY proteins:** Traditionally linked to pathogen defense, several WRKYs (e.g., OsWRKY11, AtWRKY46) also enhance drought and salt tolerance, suggesting a dual role in integrating biotic and abiotic stress responses.
2. **Heat Shock Factors (HSFs):** While best known for heat tolerance (HSFA1, HSFA2), HSFs also regulate oxidative stress responses, making them versatile protectors.
3. **NAC-MYB-WRKY interactions:** Many studies reveal that these TFs physically interact or regulate each other's expression, forming transcriptional hubs that balance growth, defense, and stress resilience.

TRANSCRIPTIONAL NETWORKS AND CROSS-TALK

The strength of plant stress responses lies in network-level regulation rather than the action of a single TF.

- ❖ Under drought stress, ABA levels rise, triggering bZIPs, NACs, and MYBs.
- ❖ Under cold stress, ICE1 activates CBF/DREB genes independently of ABA.
- ❖ WRKYs and HSFs link abiotic stress signaling with biotic defense and ROS detoxification.

This layered regulatory system allows plants to fine-tune their responses based on stress intensity, duration, and overlap with other stresses

APPLICATIONS IN CROP IMPROVEMENT

Harnessing TFs has become a promising strategy in crop improvement:

- ❖ Transgenic approaches: Overexpression of DREB, NAC, or bZIP TFs has enhanced stress tolerance in rice, wheat, maize, and tomato.

- Genome editing (CRISPR/Cas): Targeted modifications of TFs now allow precise control of stress-responsive networks. For example, editing negative regulators of ABA signaling can improve drought tolerance without yield penalties.
- Marker-assisted breeding: Natural allelic variations in TFs (such as drought-responsive NAC genes in rice) are increasingly used in breeding programs

CONCLUSION

Abiotic stress tolerance in plants is orchestrated by a concert of transcription factors that regulate stress-responsive genes through ABA-dependent and ABA-independent pathways. Key players such as DREB/CBF, NAC, bZIP, MYB, WRKY, HSF, and ICE1 act as master regulators, ensuring survival under drought, salinity, heat, and cold. Future agricultural sustainability will depend on integrating knowledge of these transcriptional networks into breeding and biotechnological strategies. By manipulating transcription factors, scientists can design crops that are not only resilient to environmental stresses but also capable of maintaining yield stability in a changing climate.

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CIRCULAR ECONOMY IN AGRICULTURE: REDUCING WASTE AND IMPROVING SUSTAINABILITY

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ABSTRACT

The agricultural sector is under growing pressure to increase food production with limited resources while minimizing environmental degradation. The circular economy offers a sustainable approach by converting agricultural waste into valuable inputs, reducing reliance on external resources, and improving soil health and farm profitability. This article examines the core principles of the circular economy, its significance in contemporary agriculture, and its contribution to waste reduction and sustainability. It also distinguishes circular economy concepts from integrated farming systems. Additionally, the article discusses future prospects, emerging technologies, and key challenges in implementation, emphasizing the importance of supportive policies, institutional coordination, and capacity building.

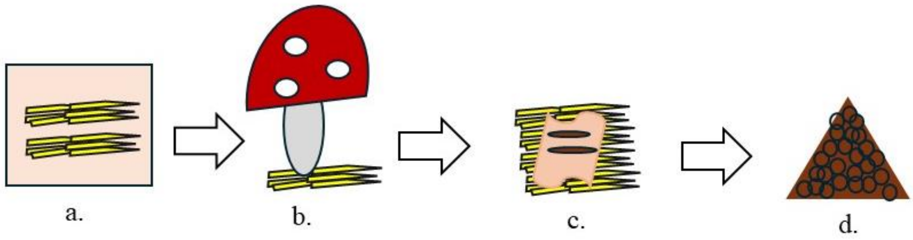
KEYWORDS: Circular agriculture, greenhouse gas mitigation, integrated farming systems, resource recycling, sustainable agriculture

INTRODUCTION

Agriculture plays a dominant role in shaping environmental conditions, contributing significantly to greenhouse gas emissions, soil degradation, and water pollution. Conventional linear production systems follow a "take–make–dispose" model that generates large quantities of waste and relies heavily on synthetic inputs. As global population continues to rise and natural resources become scarce, there is an urgent need to adopt sustainable models of production. The circular economy offers a transformative approach by emphasizing waste reduction, material reuse, and regeneration of natural systems. Within agriculture, this approach supports resource efficiency, environmental protection, and long-term productivity.

WHAT IS CIRCULAR ECONOMY?

A circular economy is an economic system designed to minimize waste and maximize the continuous use of resources through recycling, reuse, recovery, and regeneration. Unlike the linear production model, the circular approach creates closed-loop systems where by-products from one process serve as inputs for another. In agriculture, this includes recycling crop residues, generating renewable energy from waste, and returning organic matter to the soil. Circular agriculture emphasizes efficiency, low environmental impact, and the creation of value from materials traditionally considered waste. For a clear understanding of circular economy, Figure 1 is represented below.



a. Paddy straw from the field, b. Mushroom farming by using paddy straw substrate, c. Vermicomposting by using mushroom substrate and d. Final end product of compost ready for application

Figure 1. Circular cycles of the circular economy

WHY CHOOSE CIRCULAR ECONOMY IN AGRICULTURE?

Agriculture generates substantial waste from crop residues, livestock operations, and food processing activities. Rising input costs and declining soil health demand effective resource recycling. Circular practices reduce reliance on synthetic fertilizers, conserve water, enhance soil fertility, and help mitigate climate change impacts. Moreover, circularity supports economic resilience through value-added enterprises such as composting, vermicomposting, bioenergy production, and waste-based fertilizers. These practices align with global sustainability goals and agricultural development priorities.

THE PRINCIPLES GUIDING CIRCULAR AGRICULTURE INCLUDES

- **Reduce:** Systems are structured to minimize waste generation and the emphasis is on prioritizing use of regenerative and restorative resources also use of Bbiogas, solar, and biomass energy reduce dependence on fossil fuels.
- **Reuse:** This encompasses to reuse the useful parts of components or a product, wherever possible like materials such as nutrients, water, and biomass circulate within the system.
- **Recycle:** utilizing discarded material as a source of secondary resource, through extensive recycling. Organic residues are returned to ecosystems to improve soil fertility.
- **Re-manufacture:** To create new products by utilizing waste streams such as Waste materials are transformed into marketable or useful products such as compost, manure, biochar, or energy.
- **Repair/refurbish:** The aim is to preserve and extend the life of a product.

(Basic moto is to eliminate pollution, circulate products and materials and regenerative nature)

Table 1. Difference Between Linear economy, Circular Economy and Integrated Farming System (IFS)

Aspect	**Linear Economy**	**Circular Economy**	**Integrated Farming System (IFS)**
Concept Type	Follows "take, make and dispose" model	Follows reuse, recycle, reduce and regenerative model	Farm-level system integrating multiple enterprises
Resource Flow	One-way flow; resources used once and discarded	Closed-loop flow; materials reused, recycled, regenerated	Internal recycling of resources among farm components
Waste Management	Waste is largely discarded; high generation	Waste is minimized and transformed into valuable resources	Waste from one enterprise serves as input to another
Focus Area	Production efficiency without reuse	Recycling, reuse, renewal, and regeneration	Interdependence and complementarity of farm components
Scale of Operation	Global and industrial level	Engages industries, consumers, markets, and supply chains	Within the farm boundary
Environmental Impact	High pollution, resource depletion, emissions	Reduced pollution, efficient resource use	Reduced chemical use; improved soil health
Energy Use	Relies on non-renewable energy	Promotes renewable and bio-based energy	Uses biological energy cycles within the farm
Examples	Single-use plastics; chemical-intensive systems	Composting, biogas, biochar, nutrient recycling	Crop–livestock–fish integration, agroforestry

While IFS is an important farm-scale component of circular agriculture, the circular economy extends beyond the farm to include broader economic and industrial linkages. In simple words the use of the circular economy concept beyond different agricultural enterprises known as IFS.

NEED FOR CIRCULAR ECONOMY IN AGRICULTURE

- The world's population is growing with the demand for raw materials but the supply of crucial raw materials is limited.
- Extracting and using raw materials has a major impact on the environment.
- It also increases energy consumption and CO_2 emissions.
- Around 3.3 billion tons of greenhouse gases are emitted, and 1.6 billion tons of food waste is generated.

Table 2. ROLE OF ENVIRONMENTAL PROTECTION AGENCY (EPA)

Year	EPA Actions / Activities
2024	✓ June 2024: Released the *National Strategy for Reducing Food Loss and Waste and Recycling Organics* after receiving and reviewing public comments earlier in the year. ✓ September 2024: Released *Notice of Funding Opportunities* for the Solid Waste Infrastructure for Recycling and the Recycling and Education Outreach Grant Programmes. ✓ November 2024: Released the *National Strategy to Prevent Plastic Pollution* after reviewing public comments (2023).
2025	✓ 24 September 2025: EPA's Circular Economy Programme is hosting the *Annual Circular Economy Conference* at Aviva Stadium, Dublin. ✓ Conference features: presentations, case studies, interactive panel discussions, exhibition area, and networking. Focus on EU Circular Economy Act, competitiveness of circular models, and extended producer responsibility in key sectors. Showcasing *Local Circular Solutions* with enterprises presenting their circular business models. ✓ Registered as a European Sustainable Development Network event; CPD approved by Engineers Ireland and CIWM.

HOW IT WORKS?

1. Aids in Reducing Waste

Circular agriculture reduces waste by transforming it into useful products. Crop residues can be converted into compost or biochar instead of being burned, thereby improving soil carbon and reducing pollution. Livestock waste can be processed through anaerobic digestion to produce biogas and nutrient-rich digestate. Food processing waste can be used as animal feed, fertilizers, or raw materials for bio-based industries. Treated wastewater can be safely reused for irrigation. Precision agriculture technologies further decrease waste by optimizing input use.

2. Improving Sustainability

Circular practices enhance sustainability by promoting soil health, biodiversity, and ecosystem resilience. Incorporating organic matter improves soil structure, nutrient availability, and microbial activity. Renewable energy sources reduce greenhouse gas emissions and support low-carbon agriculture. Efficient water management, recycling, and precision irrigation conserve scarce resources. Collectively, these practices contribute to long-term productivity and environmental stability.

3. Impacts on Society

The circular economy benefits society by improving waste management, promoting clean environments, and opening new opportunities for rural entrepreneurship. Activities such as composting, bioenergy production, and decentralized waste processing create employment and diversify farm income. Reduced pollution from residue burning and improper waste disposal enhances public health. Sustainable food systems also improve food quality and strengthen community resilience.

FUTURE WORK

Future developments in circular agriculture will focus on technological innovation, policy integration, and market development. Waste-to-wealth technologies such as biochar production, biorefineries, and advanced composting will expand. Digital tools including artificial intelligence and the Internet of Things will enhance monitoring and precision in resource recycling. Stronger market linkages and policy frameworks will support commercialization of circular products. Research on climate-resilient circular models and nutrient recovery will be essential for large-scale adoption.

CHALLENGES

Despite its advantages, implementing circular agriculture faces several obstacles. These include limited knowledge and training, high initial investment for technologies, weak market demand for recycled products, and policy gaps. Poor waste segregation and lack of cross-sectoral coordination further hinder progress. Addressing these issues requires partnerships among governments, industries, researchers, and farming communities.

CONCLUSION

Circular economy offers a promising pathway for transforming agriculture into a sustainable and resource-efficient system. By closing nutrient loops, recovering valuable resources, and promoting regenerative practices, circular agriculture reduces environmental impacts and enhances profitability. Although challenges remain, sustained innovation, supportive policies, and community engagement will accelerate the transition. Circular agriculture is essential for ensuring long-term food security, environmental health, and resilient farming systems.

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ADVANCES IN PLANT DISEASE MANAGEMENT THROUGH GENOMIC AND PHENOMICS TECHNOLOGIES

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ABSTRACT

Innovative genomic and phenomic technologies are reshaping plant disease management by enabling rapid pathogen detection, precise resistance breeding, and early diagnosis of infections. Whole-genome sequencing reveals pathogen diversity, evolution, and virulence mechanisms, while genome editing and genetic engineering allow targeted improvement of host resistance. Integrated multi-omics approaches deepen understanding of host–pathogen interactions by linking genomic, transcriptomic, proteomic, and metabolomic changes. In parallel, hyperspectral imaging provides non-destructive, early disease detection at field scale. Collectively, these advances support sustainable, resilient disease management under evolving environmental and pathogen challenges.

KEYWORDS: Genome editing, hyperspectral imaging, multi-omics, plant disease management whole genome sequencing

INTRODUCTION

Plant diseases continue to constrain global agricultural productivity by reducing yield, compromising product quality, and threatening food security. Climate change, intensified pathogen evolution, and increasing trade activities have amplified the frequency and severity of disease outbreaks. Modern agriculture requires tools that can diagnose pathogens accurately, improve host resistance rapidly, and monitor crops continuously. In recent years, advances in genomics, molecular biology, and remote sensing have provided powerful solutions. In this article, we review five major biotechnological pillars such as whole genome sequencing, genome editing, genetic engineering, multi-omics, and hyperspectral imaging and highlights their contributions to modern plant disease management.

WHOLE GENOME SEQUENCING IN PATHOGEN SURVEILLANCE AND RESISTANCE DISCOVERY

Whole genome sequencing (WGS) has revolutionized the understanding of plant pathogens by delivering complete genetic blueprints at high speed and resolution (Biradar and Patil, 2023). WGS enables:

1. **PATHOGEN DETECTION AND DIAGNOSTICS**
   Sequencing-based detection allows identification of known, novel, or mixed infections without reliance on prior biological information. Metagenomic sequencing, in particular, has become a reliable tool for discovering emerging pathogens directly from infected host tissues.
2. **POPULATION STRUCTURE AND EVOLUTIONARY ANALYSES**
   High-resolution comparative genomics facilitates tracing pathogen spread, identifying mutation patterns, monitoring virulence evolution, and detecting fungicide or pesticide resistance alleles. Such insights support early-warning systems and guide targeted management interventions.
3. **RESISTANCE GENE DISCOVERY**
   Sequencing diverse germplasm, landraces, and wild relatives enables the identification of resistance (R) genes and quantitative trait loci (QTLs). WGS-based genome-wide association studies (GWAS) and pangenome analyses have accelerated the discovery of genetic factors underpinning host defense.

GENOME EDITING FOR PRECISION CROP PROTECTION

Genome editing technologies, particularly CRISPR/Cas systems, provide unprecedented precision for modifying genes associated with susceptibility or resistance (Patait Neha et al., 2024).

1. **FUNCTIONAL INACTIVATION OF SUSCEPTIBILITY GENES (S-GENES)**
   Targeted knockouts of S-genes limit pathogen entry or colonization. Such edits offer durable and broad-spectrum resistance without altering key agronomic traits.
2. **ENHANCEMENT OF IMMUNE SIGNALING PATHWAYS**
   Genome editing can fine-tune transcription factors, receptor-like kinases, or defense regulators that modulate plant immunity. Multiplex editing allows simultaneous modification of several genes, producing polygenic resistance.
3. **RAPID DEVELOPMENT OF CLIMATE- AND DISEASE-RESILIENT VARIETIES**
   By bypassing long breeding cycles, CRISPR accelerates the deployment of elite cultivars with improved disease tolerance, essential under rapidly shifting environmental conditions.

GENETIC ENGINEERING FOR NOVEL RESISTANCE TRAITS

While genome editing modifies endogenous genes, genetic engineering introduces new genetic elements that enhance host defense capabilities (Biradar et al., 2023).

1. **TRANSGENIC RESISTANCE TO VIRUSES, BACTERIA, AND INSECTS**

Integration of viral coat proteins, antimicrobial peptides, or insecticidal genes (such as Bt toxins) offers protection against diverse pathogens and vectors. These traits can drastically reduce dependency on pesticides.

2. **ENGINEERING PATHOGEN RECOGNITION SYSTEMS**

   Synthetic R-genes and chimeric receptors can be designed to broaden recognition of pathogen effectors, expanding the host immune landscape beyond natural limits.

3. **METABOLIC PATHWAY MODULATION**

   Transgenes that elevate production of phytoalexins, reactive oxygen species, or other defense metabolites increase basal immunity and restrict pathogen establishment.

MULTI-OMICS APPROACHES FOR DECIPHERING HOST–PATHOGEN INTERACTIONS

Multi-omics frameworks integrate multiple layers of biological information to produce a systems-level understanding of disease dynamics (Mediga and Duppala, 2023; Biradar and Namrata, 2024; Rao and Sunkad, 2024).

1. **GENOMICS AND TRANSCRIPTOMICS**

   Comparative expression profiling reveals activated or suppressed defense pathways, identifies key regulatory hubs, and supports gene-level prioritization for breeding or engineering.

2. **PROTEOMICS AND METABOLOMICS**

   Protein abundance, post-translational modifications, and metabolic signatures provide mechanistic insights into plant responses during infection. These datasets help identify biochemical pathways that govern resistance or susceptibility.

3. **SYSTEMS BIOLOGY INTEGRATION**

   Machine learning and network modeling integrate multi-omics datasets to construct regulatory networks, predict pathway interactions, and identify biomarkers for early detection or resistance breeding.

HYPERSPECTRAL IMAGING FOR EARLY AND NON-INVASIVE DISEASE DETECTION

Hyperspectral imaging (HSI) represents a major phenotyping innovation for crop health monitoring (Patil et al., 2023).

1. **SPECTRAL SIGNATURES OF DISEASE**

Infection alters pigment composition, water content, and structural properties of leaves, producing changes in spectral reflectance across visible and infrared wavelengths. HSI detects these changes long before visual symptoms appear.

2. **FIELD-SCALE MONITORING**

   Mounted on drones, tractors, or satellites, hyperspectral sensors generate high-resolution maps that identify disease hotspots, enabling precision spraying, targeted scouting, and reduced chemical inputs.

3. **INTEGRATION WITH AI AND MACHINE LEARNING**

   Spectral datasets coupled with classification algorithms support real-time disease prediction and automated decision-making systems, improving responsiveness during outbreaks.

CONCLUSION

The integration of genomic and phenomic innovations is reshaping the landscape of plant disease management. Whole genome sequencing strengthens pathogen surveillance, genome editing and genetic engineering accelerate the development of resistant cultivars, multi-omics provides a holistic understanding of disease biology, and hyperspectral imaging enables early, large-scale detection. Together, these complementary tools support a shift toward predictive, precise, and sustainable plant protection strategies. As these technologies continue to advance, they will play a critical role in safeguarding global food systems against evolving pathogen threats.

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ROLE OF SOIL MICROBES IN MINERAL TRANSFORMATION FOR PLANT NUTRITION

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ABSTRACT

Modern agriculture faces yield stagnation despite heavy fertilizer use, resulting in soil degradation and environmental harm. A key cause of reduced crop response is that many essential nutrients exist in insoluble or bound mineral forms, limiting plant availability. Microbe–mineral interactions help address this constraint by regulating nutrient transformations in soil. Microbial processes enhance macro- and micronutrient availability in the rhizosphere through mineral dissolution, transformation, and precipitation. Processes such as biological nitrogen fixation, phosphorus solubilisation, potassium mobilisation, and iron chelation improve nutrient uptake and use efficiency. Additionally, these interactions restore soil fertility and support bioremediation via toxic metal immobilization, offering a sustainable pathway to improved productivity and soil health.

KEYWORDS: Biofertilizers, bioremediation, heavy metal detoxification, nutrient transformation, soil-plant-microbes interactions, soil fertility

INTRODUCTION

Minerals are the basic building blocks of the Earth's crust and serve as the primary source of essential nutrients for plant growth. Mineral nutrients are vital for crop growth and productivity, as they regulate numerous physiological and biochemical processes in plants. Macronutrients like nitrogen (N), phosphorus (P) and potassium (K), as well as micronutrients like zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn) are essential to many plant metabolic processes (Jabborova et al., 2021). These nutrients are necessary for essential physiological processes in plants, including respiration, photosynthesis, and enzymatic activity, all of which have a direct impact on crop quality, growth, and yield. In modern agriculture, chemical fertilizers are widely used to supply essential nutrients to crops. However, increasing evidence suggests that fertilizer application alone does not guarantee adequate nutrient uptake by plants. In many soils, nutrients remain bound in insoluble mineral complexes, which limit their direct availability to plant roots. Although minerals are abundant in soils, their contribution to plant growth largely depends on biological processes that govern nutrient transformation and release. Soil microorganisms play a crucial role in mobilizing these mineral-bound nutrients and making them available for plant uptake (Dong et al., 2022). Soil microbes enhance nutrient availability through their metabolic activities, including mineral dissolution and transformation processes. Through mineral solubilization, microorganisms convert insoluble mineral forms into bioavailable nutrients that plants can easily absorb (Kapadia et al., 2022). The secretion of organic acids, siderophores, and other chelating compounds further facilitates the solubilization of mineral nutrients and their assimilation by plants (Ribeiro et al., 2020).

It has been demonstrated that overuse of chemical pesticides and fertilisers negatively impacts the environment, microbial diversity, and soil health. As a result, it is becoming more and more important to employ sustainable farming methods that support beneficial microbes as affordable substitutes for agrochemicals. Thus, understanding the microbe–mineral interactions is essential for improving nutrient use efficiency, enhancing crop productivity, and maintaining soil health.

SOIL MINERALS AS NUTRIENT RESERVOIRS IN AGROECOSYSTEMS

Soil acts as the primary reservoir of both macro- and micronutrients essential for crop growth and productivity. Numerous minerals comprising nitrogen (N), potassium (K), phosphorus (P), magnesium (Mg) , calcium (Ca),) Iron (Fe, zinc (Zn), and manganese (Mn) are created in soils through long-term geological processes. These soil minerals are important sources of nutrients for plants and are essential for preserving soil fertility in agroecosystems. Despite their abundance, most soil minerals remain unavailable to plants because nutrients are tightly bound within mineral structures. Phosphorus is commonly fixed with iron or aluminium, while potassium is trapped within silicate minerals such as mica and feldspar. Due to these chemical constraints, even soils with high total nutrient content often fail to supply adequate nutrients to crops, resulting in poor nutrient uptake by plants (Kapadia et al., 2022). Natural mineral weathering is a slow process and, by itself, cannot meet the nutrient demands of modern cropping systems. Microorganisms in the soil are essential for speeding up the release of nutrients and the transformation of minerals. Microbes boost nutrient availability and mineral solubility in the soil solution by secreting organic acids, siderophores, and other metabolites. These soil–plant–microbe interactions significantly improve nutrient cycling, enhance nutrient use efficiency, and support sustainable soil health management in modern agriculture.

MICROBIAL PROCESSES GOVERNING MINERAL TRANSFORMATION

Interactions between microorganisms and soil minerals play a crucial role in driving biological processes and regulating nutrient cycling in soils (Ortiz-Castillo et al., 2021). Microbe–mineral interactions influence the mobility, availability, and transformation of nutrients and metals in agroecosystems. Various microbial processes such as mineral dissolution, precipitation, and transformation alter the chemical form of minerals and control nutrient dynamics in soils. Understanding these microbe-mediated processes is essential for improving soil fertility, nutrient availability, and sustainable agricultural production.

A) MICROBIAL MINERAL DISSOLUTION

The process of interactions between the solid mineral phase and the soil solution that leads to the chemical breakdown of minerals is known as microbial mineral dissolution. Soil microorganisms accelerate the dissolution of solid minerals through various biochemical reactions. This process primarily involves the release of organic acids and chelating compounds by microbes, which weaken chemical bonds within mineral structures and promote nutrient release.

Under iron-limited conditions, siderophore-producing microorganisms increase the availability of iron by forming stable complexes with ferric iron, thereby enhancing its uptake by plants (Ahmed and Holmstrom, 2014). Further encouraging mineral dissolution and nutrient availability in the rhizosphere, several bacteria also convert ferric iron (Fe^{3+}) to the readily soluble ferrous form (Fe^{2+}).

B) MICROBIAL MINERAL PRECIPITATION

By lowering metal toxicity in agricultural soils, microbial mineral precipitation is essential to soil detoxification and bioremediation. Through metabolic processes like oxidation, reduction, and biomineralization, some bacteria convert soluble metals into stable, insoluble mineral forms. By immobilising excess and hazardous metals, this method limits their uptake by plants and stops them from building up in the soil solution. Sulphate-reducing bacteria, which produce sulphide ions as metabolic byproducts, are a typical example. Metal sulphide minerals are created when these sulphide ions react with metals like iron and cadmium (Nnaji et al., 2024). By efficiently transforming soluble hazardous metals into insoluble forms, microbe-mediated mineral precipitation helps to promote soil health and sustainable agricultural management by eliminating them from soil and water systems.

EFFECTS OF MINERAL SOLUBILIZATION ON CROP NUTRITION

Plant–microbe interactions play a significant role in improving crop yield, biomass production, and resilience to both biotic and abiotic stresses. These interactions enhance the availability of essential nutrients to plants, thereby improving crop nutrient status, growth, and overall productivity. Microbe-mediated mineral solubilization is a key process through which nutrients locked in soil minerals are converted into plant-available forms, supporting efficient nutrient uptake and sustainable crop production.

a) BIOLOGICAL CONVERSION OF ATMOSPHERIC NITROGEN (N_2)

Nitrogen (N_2) in the atmosphere cannot be directly used by plants. When the nitrogenase enzyme complex is present, nitrogen-fixing microorganisms like Frankia and rhizobacteria transform atmospheric nitrogen into ammonium (NH_4^+). In addition to providing plant-available nitrogen, this biological nitrogen fixation lessens reliance on artificial nitrogen fertilisers and supports environmentally sound agriculture practices.

b) SOLUBILIZATION OF MINERAL-BOUND PHOSPHORUS

Phosphorus is a vital nutrient that plants need for different physiological processes, including photosynthesis, ATP generation, and genetic material synthesis. Despite being prevalent in soils, phosphorus is frequently found in less soluble forms like calcium or aluminium phosphates, which restrict its availability to crops. Organic acids like citric, oxalic, and gluconic acids are released by phosphate-solubilizing microbes like Bacillus and Pseudomonas, which dissolve these complexes and increase the amount of phosphorus available to plants (Miliute et al., 2015).

c) POTASSIUM MOBILIZATION

In plants, potassium is essential for osmoregulation and stress tolerance. Potassium is mostly found in bonded forms in feldspar, mica, and other silicate minerals in soils, which makes it difficult for plants to absorb (Baba et al., 2021). Potassium-solubilizing fungi like *Aspergillus* and bacteria such as *Bacillus* mobilize potassium through acidification and chelation processes, releasing it into the soil solution for plant absorption.

d) IRON CHELATION

Iron is predominantly present in soils as insoluble ferric (Fe^{3+}) compounds, especially under aerobic and alkaline conditions. Rhizobacteria such as *Rhizobium* and *Pseudomonas* produce siderophores that chelate ferric iron and facilitate its conversion into the more soluble ferrous (Fe^{2+}) form. This process enhances iron uptake by plants, prevents iron deficiency symptoms, and can also suppress soil-borne pathogens through competitive iron sequestration.

e) SOLUBILIZATION OF MICRONUTRIENTS

Micronutrients such as zinc are often present in insoluble forms in soils, leading to widespread deficiencies in crops. Zinc-solubilizing bacteria, including *Bacillus* and *Pseudomonas*, mobilize micronutrients through acidolysis, organic acid production, and siderophore secretion. These microbial processes enhance the solubilization and availability of micronutrients, supporting enzymatic activity, photosynthesis, and overall crop growth.

CROP RESILIENCE TOWARDS STRESSES

Soil microbial communities play a significant role in enhancing crop resilience against both biotic and abiotic stresses by regulating plant stress-responsive hormones and physiological processes. Microbe-mediated mechanisms help plants tolerate adverse conditions such as drought, salinity, nutrient deficiency, and pathogen attack. As summarized in Table 1, various microbial processes contribute significantly for improving crop resilience under severe environmental conditions.

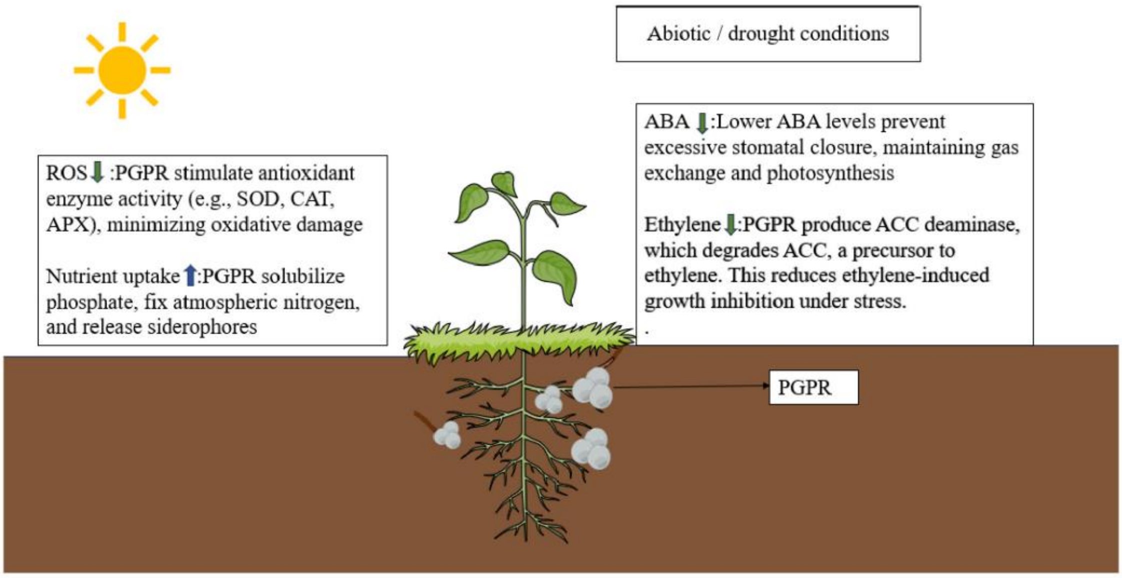

Figure 1 The graphic illustrates how plant growth-promoting rhizobacteria can reduce stress and boost plant development during drought (Pradhan et al., 2025).

MICROBE-MEDIATED IMPROVEMENT OF ROOT GROWTH

For plants to effectively absorb nutrients and adapt to stress, root architectural characteristics such as root hair elongation, lateral root branching, and overall root length are crucial. Soil microorganisms, especially arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR), have a significant impact on these characteristics. Under both normal and stressful situations, a plant's ability to explore soil nutrients and water is mostly determined by the amount of root hairs, branching density, and root elongation. By spreading fungal hyphae past the root surface, arbuscular mycorrhizal fungi improve nutrient uptake, particularly phosphorus, and increase the root absorptive area (Rawat et al., 2020).

Similar to this, phytohormones like indole-3-acetic acid (IAA), which increase root surface area and promote root elongation, are released by rhizobacteria that promote plant growth.

Table:1 Microbial strategies for reducing abiotic stress.

Abiotic stress	Microbiological mechanism	Important micro-organisms	Impact on the plant	Reference
Drought	Lower ethylene levels enhance vital antioxidant enzymes and ABA regulation.	*Bacillus subtilis, Glomus intraradices*	Improves drought resistance and water retention	Ahmad et al. (2022)
Salinity	Ionic balance and antioxidants	*Pseudomonas, Azospirillum*	Lessens oxidative stress and ion toxicity	(Ayuso-Calles et al., 2020)
Heavy metals	Metal transformation, biosorption, and siderophores	*Pseudomonas, Bacillus, and Azospirillum*	Enhances phytoremediation and reduces metal toxicity	(Saha et al., 2016)

Both overall plant vigour and the efficiency of nitrogen uptake are enhanced by these modifications. Additionally, secondary metabolites, carbohydrates, and amino acids secreted by plant roots promote the development and activity of nearby microbial populations in the rhizosphere. Furthermore, root architectural features have a significant impact on microbial interactions. While more lateral root branching offers more places for microbial adhesion, well-developed axial roots encourage microbial colonisation by increasing carbon deposition. Diverse microbial communities grow as a result, improving nutrient mobilisation, especially in areas with low phosphorus (Chen and Liu, 2024).

Overall, plant–soil–microbe interactions not only improve soil health but also optimize root architecture, leading to enhanced crop productivity even under resource-limited conditions (Saha et al., 2016).

CONCLUSION

For reducing dependency on chemical fertilisers, microbe-mediated nutrient transformation provides significant opportunities. Beneficial soil microorganisms enhance the availability of mineral-bound nutrients, thereby promoting nutrient recycling and improving nutrient use efficiency. This helps in fulfilling crop nutrient demands with lower dependency on external fertiliser inputs. Such an approach not only reduces the cost of production for farmers but also minimizes adverse environmental impacts. By providing biologically fixed nitrogen, solubilising phosphorus and potassium, and mobilising vital micronutrients, microbial biofertilizers contribute significantly to sustainable nutrient management. Their application preserves soil biological activity while promoting balanced plant nutrition. While including microbial inputs helps restore soil health and enhance soil organic matter, aggregation, and nutrient cycling, continuous application of chemical fertilisers alone can deteriorate soil structure and microbial diversity. The advantages of organic, biological, and chemical nutrient sources are combined when microbial biofertilizers are incorporated into the framework of Integrated Nutrient Management (INM). Long-term soil fertility, consistent agricultural productivity, and environmental sustainability are all guaranteed by this strategy. Therefore, developing robust and resource-efficient agronomic systems requires the adoption of microbe-based techniques.

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TOXIC FOOT PRINT OF CHEMICALS: IMPACTS ON SOIL QUALITY, WATER RESOURCES, AND BIOTIC COMMUNITIES

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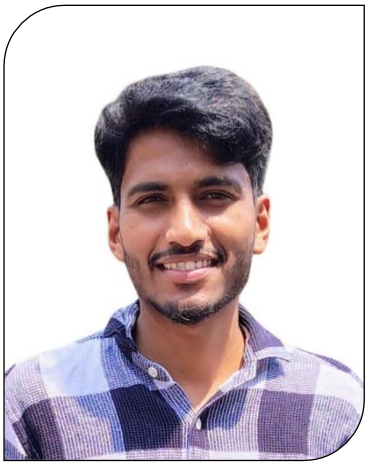

ABSTRACT

The green revolution in India, launched in the mid-1960s, represented a pivotal shift in agricultural production by introducing high-yielding, input-responsive crop varieties supported by expanded irrigation and intensive nutrient management. This transformation helped convert India from a food-deficient nation into a major food producer. However, the productivity gains were largely dependent on extensive use of synthetic fertilizers, pesticides, and herbicides. Over time, their indiscriminate and continuous application has led to ecological challenges, including pest resistance, secondary pest resurgence, chemical residues, non-target toxicity, and declining soil health. Consequently, systematic risk assessment is essential for sustaining agricultural productivity and environmental safety.

KEYWORDS: Green revolution, synthetic fertilizers, pesticides, herbicides, toxicity

INTRODUCTION

Agrochemicals—including fertilizers, pesticides, herbicides, fungicides, and plant growth regulators—have been central to increasing agricultural productivity and food security since the Green Revolution introduced input-responsive high-yielding varieties (Pingali, 2012). However, their intensive and prolonged use has fostered chemical-dependent farming systems with significant environmental consequences. After application, agrochemicals disperse through runoff, leaching, volatilization, and atmospheric transport, leading to accumulation in soil, water, and air. Excess nitrogen fertilization causes soil acidification, nutrient imbalance, and microbial disruption, while persistent pesticides and associated contaminants reduce soil biodiversity, suppress beneficial organisms, and impair long-term soil fertility and ecosystem functioning (Tilman et al., 2002).

Agrochemical residues also contaminate water bodies and the atmosphere, resulting in groundwater nitrate pollution, aquatic toxicity, eutrophication, biodiversity loss, and emissions of ammonia, nitrous oxide, volatile organic compounds, and particulate matter. These pollutants degrade air quality and contribute to climate change. Biological systems, including pollinators, natural enemies, wildlife, and humans, are vulnerable to acute and chronic toxicity, such as reproductive, endocrine, and neurological disorders (Kim et al., 2017; Chandrasekar et al., 2022). These concerns underscore the need for sustainable strategies, including integrated nutrient and pest management, ecological intensification, and safer agrochemical alternatives to balance productivity with environmental and human health protection.

HOW AGROCHEMICALS REACH ENVIRONMENT?

Agrochemicals enter the environment through multiple interconnected pathways immediately after application, including spray drift, volatilization, runoff, leaching and soil erosion. During spraying, off-target drift and volatilization transport chemicals into the atmosphere, where they may undergo long-range movement before redeposition. Rainfall or irrigation facilitates surface runoff, carrying dissolved chemicals and pesticide-bound soil particles into nearby water bodies, while water-soluble compounds such as nitrates and certain pesticides leach

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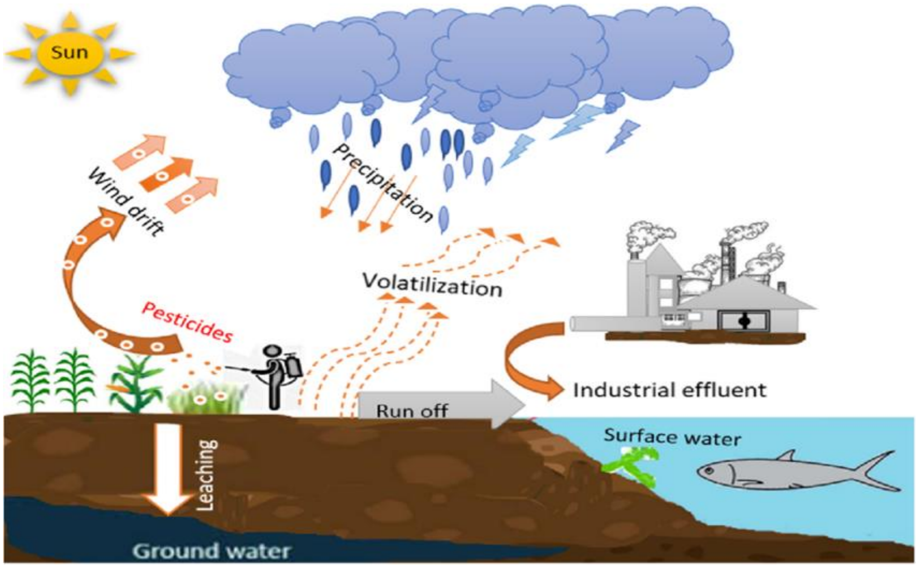

Figure. 1: Agrochemicals reaching environment

through soil profiles into groundwater. Many agrochemicals adsorb to clay and organic matter and are subsequently transported with eroded sediments, accumulating in aquatic systems and food webs; improper handling, spills and unsafe disposal further intensify soil and water contamination, often contributing to eutrophication. The environmental fate and mobility of these chemicals are governed by their physicochemical properties (solubility, sorption coefficient, vapor pressure and persistence) and soil characteristics (texture, organic carbon, pH and microbial activity). Persistent residues and metabolites can remain in soils and sediments for extended periods, disrupting microbial processes, impairing nutrient cycling and posing chronic risks to ecosystems and human health, demonstrating that agrochemicals rarely remain confined to their intended targets

BEYOND THE FIELDS: HOW AGRICULTURE BECAME A MAJOR DRIVER OF AIR POLLUTION

Agriculture contributes substantially to air pollution through direct emissions and secondary pollutant formation. Field operations and residue burning release large quantities of particulate matter, while diesel-powered machinery emits NO_2, black carbon, and primary PM, degrading air quality (Thai et al., 2024). Fertilizers, livestock, and agrochemicals are major sources of ammonia and VOCs, which promote secondary aerosol and ozone formation (Wyer et al., 2022). Nitrogen fertilization further drives nitrous oxide (N_2O) emissions, a potent greenhouse gas, with emission levels varying by crop, fertilizer type, and nitrogen dose, as shown in Table 1. These differences reflect interactions among fertilizer chemistry, soil aeration, and crop nitrogen dynamics, underscoring the need for precision nutrient management to mitigate atmospheric impacts (Pathak et al., 2010).

Table 1: Nitrous oxide emission from different crops

Crop	Fertilizers	N dose (kg ha^{-1})	N_2O emission (kg N ha^{-1})
Rice	Urea	140	0.06
	Ammonium sulphate	140	0.23
	Potassium nitrate	120	0.19
Wheat	Urea	140	0.71
Maize	Urea	120	0.64
Pigeon pea	Urea	40	0.37
Groundnut	Urea	60	0.46
Mustard	Urea	80	0.56
Chickpea	Urea	40	0.49

The standard limits of heavy metals in soils, fruits, and vegetables presented in Table 2 illustrate the chemical footprint of agrochemical use and associated inputs such as fertilizers, pesticides, wastewater, and soil amendments. Metals such as Pb, Cd, Hg and As**,** which often originate from phosphate fertilizers, synthetic pesticides, soil amendments and industrial contamination, persist in soil due to their low mobility and accumulate in edible plant parts, sometimes exceeding international permissible limits.

Indian and EU soil standards (e.g., Pb 250–500 mg/kg; Cd 3–6 mg/kg) and WHO/FAO food limits (Pb 5.0 mg/kg; Cd 0.2 mg/kg; Hg 0.03 mg/kg; As 0.5 mg/kg) underline the toxicological concern associated with chronic metal exposure. Essential micronutrients such as Zn, Cu, Mn and Ni**,** though required in trace amounts, can also reach phytotoxic levels when repeatedly added through agrochemicals, creating oxidative stress, suppressing enzyme function and impairing crop performance. The comparison of regulatory thresholds thus reflects how agrochemical-driven heavy-metal loading leaves a measurable chemical footprint, influencing soil health, food safety and long-term ecological sustainability (Mahawari et al., 2022).

Table 2: Standard levels of selected heavy metals (mg/kg) in soil, fruits and vegetables

Heavy metals	**Soil**		**Fruits and vegetables**	
	Indian Standard[55]	**EU Standard**[56]	**Indian standard**[55]	**WHO/FAO Standard**[75]
Pb	250-500	60	2.5	5.0
Cd	3-6	1	1.5	0.2
Hg	-	0.5	-	0.03
As	-	5	-	0.5
Zn	300-600	200		
Ni	750-150	50		
Cu	135-270	100		
Mn	-	-		
Cr	-	100		

A study conducted in the industrialized region of Solapur, Maharashtra, assessed heavy-metal contamination in 24 types of vegetables and fruits using ICP-MS and evaluated associated human health risks (Mahawari et al., 2022). The findings revealed detectable concentrations of Pb, Cd, As and Hg in edible crops, reflecting contamination of native soils influenced by agrochemical use and wastewater irrigation. Mean concentrations in vegetables Pb (0.344 mg kg^{-1}), Cd (0.043 mg kg^{-1}), As (0.004 mg kg^{-1}) and Hg (0.095 mg kg^{-1}) were close to or exceeded WHO/FAO permissible limits, with mercury levels notably surpassing safe thresholds. Although fruits showed comparatively lower accumulation, the presence of trace metals confirmed active soil–plant transfer and biomagnification pathways. The study highlights a growing disparity between regulatory standards and field realities, emphasizing the need for integrated nutrient–toxicant management and continuous monitoring to safeguard food safety and public health.

The Bureau of Indian Standards (BIS) drinking-water guidelines provide critical thresholds for chemical contaminants with known health implications, as summarized in Table 3. Parameters such as fluoride, nitrate, arsenic, and uranium pose significant public health risks when concentrations exceed acceptable limits, leading to dental and skeletal fluorosis, methemoglobinemia, carcinogenic effects, and renal toxicity. The absence of permissible relaxation for contaminants like nitrate, arsenic, and uranium highlights their toxicological severity. Electrical conductivity, though not a direct toxicant, serves as an indicator of salinity stress linked to cardiovascular complications. Together, the regulatory limits in Table 3 underscore the importance of sustained groundwater monitoring and mitigation to safeguard drinking-water quality.

Table 3: Indian Bureau of standards guidelines for contaminants levels in drinking water

Analyte	Unit	Acceptable limit	Permissible limit	Health effects
Chloride (Cl)	Mg/L	250	1000	Eye/nose irritation; stomach discomfort
Fluride (F)	Mg/L	1	1.5	Bone disease; children may get mottled teeth
Iron (Fe)	Mg/L	1	None	Anesthetic effect; promtes iron bacteria
Nitrate (NO_3)	Mg/L	45	None	Blue baby syndrome
Arsenic (As)	µg/L	10	No relaxation	Skin damage; increased risk of cancer
Uranium (U)	µg/L	30	No relaxation	Increased risk of cancer; kidney toxicity
Electrical conductivity (EC)	µS/cm at 25^0 C	750	3000	Anaesthetic effect; cardiovascular complication

BEYOND TARGET PESTS: BROAD-SPECTRUM AGROCHEMICAL EFFECTS ON BENEFICIAL INSECTS

Agrochemical exposure causes both acute and sub-lethal effects on pollinators, including honey bees and wild bees, resulting in impaired navigation, reduced foraging efficiency, and disruptions in learning and memory (Figure 2). Field and laboratory studies from India indicate that neonicotinoids and other commonly used insecticides reduce forager return rates, decrease pollen and nectar loads, and alter foraging behavior in *Apis* spp., ultimately lowering colony food reserves and fitness. Sub-lethal effects—such as compromised learning, reduced motor activity, and altered caste or brood development—often occur at concentrations below lethal thresholds. Consequently, repeated or chronic exposure can drive population-level declines even in the absence of visible mass mortality events (Chandrasekar et al., 2022).

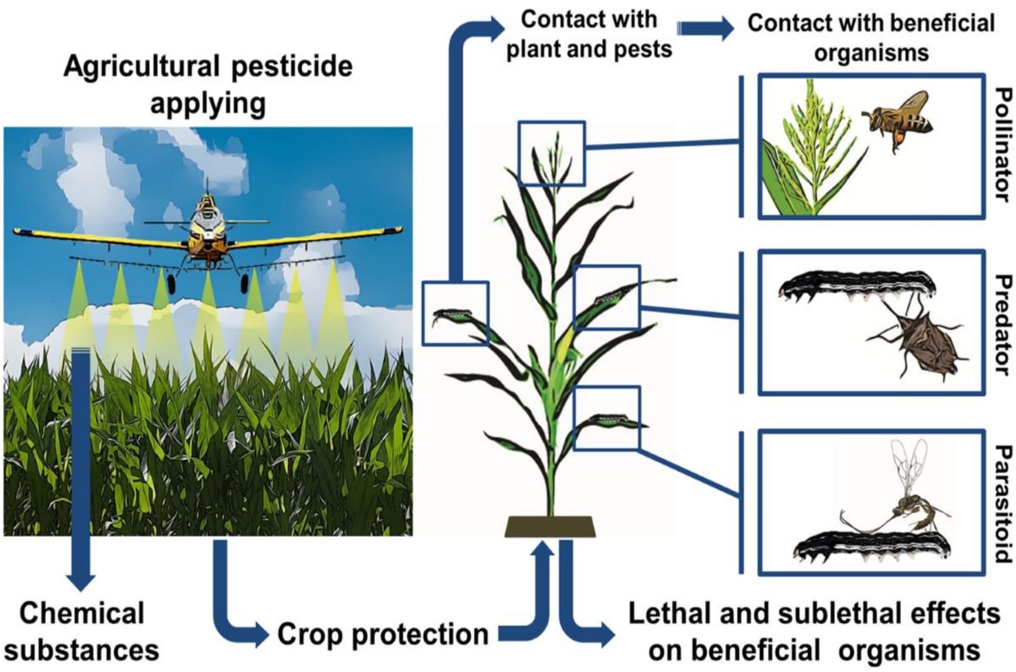

Figure 2: Agrochemicals effect on beneficial insects

PESTICIDES IN HONEY

Honey possesses multifaceted beneficial properties; however, environmental pollution and unregulated apicultural practices have contributed to its contamination. A study conducted in northern India employed the QuEChERS extraction method followed by chromatographic analysis using GC-μECD/FTD and GC-MS to determine 24 pesticide residues in 100 raw honey samples collected from diverse floral sources. Matrix-matched calibration demonstrated good selectivity and linearity ($r^2 > 0.99$), with limits of detection below 9.1 ng g^{-1} for all pesticides except monocrotophos (21.3 ng g^{-1}). Mean recoveries ranged from 86.0 to 107.7% with relative standard deviations below 20%, confirming method reliability. Pesticide residues were detected in 19.0% of samples, with dichlorvos, monocrotophos, profenofos, permethrin, ethion, and lindane being most prevalent. Honey from cotton, sunflower, and mustard crops showed significantly higher contamination (33.3%; $p < 0.05$) than honey from natural vegetation (13.5%), highlighting the need for systematic monitoring of pesticide residues in apicultural landscapes (Kumar et al., 2018).

TOXICOLOGICAL IMPLICATIONS OF AGROCHEMICAL USE ON HUMAN HEALTH

Pesticides are widely used to protect crops and commercial commodities, with nearly 1.8 billion people engaged in agriculture globally (Kumar et al., 2023). Their application reduces yield losses by controlling weeds, insects, and pathogens; however, increasing concern exists regarding their adverse effects on human health due to broad-spectrum and non-target toxicity. Human exposure occurs through occupational handling, spray drift, volatilization, contaminated food and water, with toxicity influenced by chemical properties, exposure duration, and environmental conditions (Kim et al., 2017). Since most diseases have multifactorial origins, no population group is entirely immune to pesticide-related health impacts. Globally, an estimated 385 million cases of occupational pesticide poisoning occur annually, resulting in approximately 11,000 deaths and affecting nearly 44% of the agricultural workforce, highlighting the substantial public health burden (Rogers & Rogers, 2024).

Chronic pesticide exposure has been linked to a wide range of health disorders, including neurological impairments due to cholinesterase inhibition, respiratory diseases such as asthma and chronic bronchitis, and dermal and ocular irritation among farm workers. Long-term exposure is also associated with endocrine disruption, reproductive toxicity, immune dysfunction, and increased risks of cancers, particularly leukemia and lymphoma. Additionally, bioaccumulation of pesticide residues can impair liver and kidney function through sustained metabolic stress. Collectively, these findings demonstrate that prolonged pesticide exposure affects multiple organ systems and underscores the need for safer handling practices, reduced chemical dependence, and strengthened occupational health protections in agricultural systems (Shekar et al., 2024).

CONCLUSION

The evidence synthesized across soil, water, air, biotic systems, and human health clearly demonstrates that agrochemicals leave a persistent and multidimensional toxic footprint in modern agriculture. Although fertilizers and pesticides have played a critical role in enhancing crop productivity and food security, their long-term and often unregulated use has led to nutrient imbalances, greenhouse gas emissions, heavy-metal accumulation, groundwater contamination, air-quality degradation, biodiversity loss, and rising chronic disease burdens among farming communities. Interactions among agrochemical properties, soil–water processes, atmospheric transport, and biological systems generate complex contamination cascades that extend well beyond the field scale. Mitigating these impacts requires a transition toward precision nutrient management, integrated pest management (IPM), safer formulations, improved regulatory oversight, and strengthened farmer awareness. Collectively, these measures can reduce ecological toxicity, protect human health, and align agricultural intensification with long-term environmental sustainability.

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PROBIOTICS: A BOON FOR MANAGEMENT OF CALF DIARRHEA

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ABSTRACT

Calf diarrhea is a major health and economic challenge in pre-weaned calves, particularly in India, leading to poor growth, high morbidity, and mortality. The first two weeks of life are critical due to environmental stress, dietary transitions, and immature immunity, increasing susceptibility to enteric pathogens such as Escherichia coli and Salmonella spp. Probiotics, especially Lactobacilli, play a vital role in stabilizing gut microbiota, suppressing pathogens, and enhancing immune function. Early probiotic supplementation offers a safe and effective strategy for preventing calf diarrhea and improving overall calf health and productivity.

KEYWORDS: Calf diarrhea, gut microbiota, lactobacillus, pre-weaned calves, probiotics

INTRODUCTION

The calf represents the foundation of the future dairy herd, and its health is a critical determinant of productivity, profitability, and animal welfare. At birth, the gastrointestinal tract (GIT) of the calf is sterile and is rapidly colonized by microorganisms from the dam and surrounding environment. During the first month of life, the intestinal microbiota remains highly unstable, making calves particularly susceptible to pathogenic colonization and gastrointestinal disorders such as diarrhea. These disorders reduce nutrient absorption and digestion efficiency, leading to growth retardation and increased mortality.

Calf diarrhea (scours) is a multifactorial disease with serious economic and welfare implications. It is estimated that nearly 50% of pre-weaning calf mortality is attributable to acute diarrhea. Although several infectious agents—including rotavirus, coronavirus, and *Cryptosporidium*—may be present in healthy calves without causing disease, pathogens such as enterotoxigenic *E. coli* and *Salmonella* spp. often trigger outbreaks when introduced into susceptible environments. In this context, probiotics offer a biologically safe and effective approach for controlling diarrhea and improving gut health in calves.

PROBIOTICS: CONCEPT AND SIGNIFICANCE

The term *probiotic* was introduced by Lilly and Stillwell in 1965 to describe growth-promoting substances produced by microorganisms. Probiotics are defined by FAO/WHO and ISAPP as "live microorganisms which, when administered in adequate amounts, confer a health benefit on the host." These organisms help maintain microbial balance in the GIT, secrete antimicrobial compounds, modulate immune responses, and enhance nutrient utilization. Probiotics are generally recognized as safe (GRAS); however, their efficacy must be validated under practical farm conditions.

BENEFITS OF PROBIOTICS IN CALVES

Probiotic supplementation in calves provides multiple benefits: -

- Improved gut health and immunity by enhancing intestinal barrier integrity and pathogen resistance.
- Reduced incidence and duration of diarrhea, thereby lowering mortality and antibiotic dependence.
- Enhanced growth performance and feed efficiency, reflected in improved average daily gain and nutrient utilization.
- Improved stress tolerance during weaning, dietary transitions, and transport.
- Better rumen fermentation, leading to increased production of beneficial volatile fatty acids.

CURRENT STATUS OF CALF DIARRHEA

Calf diarrhea remains a major cause of morbidity and mortality worldwide. Digestive disorders affect approximately 38.5% of pre-weaning dairy calves. According to the National Animal Health Monitoring System (USA), diarrhea accounts for nearly 39% of calf deaths within the first three weeks of life. In India, calf mortality rates range from 12.5% to 30% under field conditions, far exceeding the economically acceptable level of 3–5% observed in developed dairy systems.

CALF DIARRHEA AND INFECTIOUS AGENTS

Calf diarrhea is commonly caused by mixed infections involving *Rotavirus*, *Coronavirus*, *Escherichia coli*, *Salmonella* spp., and *Cryptosporidium parvum*. Infection with one pathogen often predisposes calves to secondary infections. Rotavirus is the most frequently detected pathogen, followed by *Cryptosporidium* and coronavirus. *Salmonella*, particularly *S. dublin*, is often associated with outbreaks in calf-rearing units sourcing animals from multiple origins.

MICROBIOTA MANIPULATION STRATEGIES

The calf GIT is highly vulnerable to dysbiosis during early life. Preventive strategies focus on early microbiota modulation through probiotic supplementation, fecal microbiota transplantation (FMT), and rumen microbiota transplantation (RMT). Common probiotic genera include *Lactobacillus* and *Bifidobacterium*, while marker bacteria for gut normalization include *Selenomonas*, *Prevotella*, *Succinivibrionaceae*, and *Porphyromonadaceae*.

FEEDING OF PROBIOTICS

A daily intake of 10^9–10^{10} CFU of viable probiotic cells has been shown to positively influence calf health. Effective strains for diarrhea control include *Lactobacillus plantarum* CDR2, *L. rhamnosus* CRD9, *L. acidophilus* 27SC, *Bifidobacterium pseudolongum*, and *Bacillus subtilis*, administered singly or in combination.

TIMING OF PROBIOTIC ADMINISTRATION

Probiotics can be administered from day one of life to promote early microbial establishment. Optimal use includes daily supplementation in milk or milk replacer, targeted use during stressful periods such as weaning or heat stress, and supportive therapy during early signs of digestive disturbances.

MECHANISM OF ACTION OF PROBIOTICS

Probiotics alleviate diarrhea through multiple mechanisms, including competitive exclusion of pathogens, production of antimicrobial compounds, strengthening of intestinal epithelial barriers, immunomodulation, production of short-chain fatty acids, and regulation of gut motility.

CONCLUSION

Probiotics represent an effective, safe, and sustainable strategy for the prevention and management of calf diarrhea. By stabilizing intestinal microbiota, enhancing immune responses, and improving nutrient utilization, probiotics significantly reduce disease incidence and improve growth performance in pre-weaned calves. Early-life supplementation is particularly critical, as it supports the development of a resilient gastrointestinal ecosystem during a highly vulnerable period. Incorporating probiotics into calf-rearing programs can reduce reliance on antibiotics, lower mortality rates, and improve overall herd productivity. Consequently, probiotics should be considered an integral component of modern, health-oriented dairy management systems.

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CONSERVATION AGRICULTURE: PROTECTING SOIL FOR FUTURE GENERATIONS

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ABSTRACT

In 2024, India's population reached 1.44 billion, growing at 0.92%, placing immense pressure on agriculture to meet food demands amid resource constraints inherited from the Green Revolution. Climate change further threatens food security by intensifying stress on land under intensive cultivation. Conservation agriculture (CA) offers a sustainable pathway by improving soil health and productivity through minimal soil disturbance, permanent soil cover, and diversified crop rotations. However, CA is knowledge-, machinery-, and herbicide-intensive, requiring strong institutional support. Widespread adoption demands coordinated efforts from farmers, researchers, and policymakers, particularly in arid regions, to achieve long-term agricultural sustainability.

KEYWORDS: Crop residue, greenhouse gases, soil health, sustainable agriculture, zero tillage

INTRODUCTION

The Green Revolution of the 1960s resulted in enhanced agricultural output and the eradication of significant foodgrain shortages in India. Green revolution primarily involved growing of improved varieties of rice and wheat, use of high doses of chemical fertilizers and other agrochemicals, and intensive irrigation facilities. This was also accompanied by the other cultivation methods, which are maximum tillage, clean cultivation with removal of crop residues and residue burning, crop rotations mostly involving cereals, and the elimination of fertility-restoring leguminous plants and oilseed crops in the highly productive Indo Gangetic plain zone of the country. However, the transformation of 'traditional animal-based subsistence farming' to 'intensive chemical- and tractor-based modern agriculture' has led to a raised issues questioning sustainability of system. The implementation of these technologies has resulted in diminished resource use efficiency, deteriorating soil health, eutrophication of ponds, lakes and other water sources, increasing cost of production, air pollution and reduced profitability.

Major concern nowadays primarily in Indo-Gangetic Plains (IGP) is ignition of fossil fuels and residue burning and puddling for the rice cultivation leading to increased emission of greenhouse gases (GHGs), leading to climate change and global warming. Conservation agriculture (CA) is a new model in resource management for mitigating the problems associated with these modern cultivation practices. It is a comprehensive strategy for enhancing soil health and productivity. In order to prevent biological disruption, CA is known to optimize the use of external inputs (agrochemicals), decrease tillage, and improve biological and natural processes both above and below ground. All system components work better in CA systems, and plants are stronger, efficient, and resilient.

PRINCIPLES OF CONSERVATION AGRICULTURE

1. Minimum soil disturbance through no-tillage or reduced tillage: though zero-till is ideal, CA can involve controlled tillage where no more than 20-25 percent of the soil is disturbed.
2. Permanent maintenance of soil mulch by retaining crop residues or cover crops on the field: A minimum of 30 percent permanent organic soil cover is maintained as per CA definitions.
3. Diversification of cropping systems through proper crop rotation: crop rotation and intercropping using legumes are recommended.

Conservation agriculture is an integrated approach, requiring high knowledge and site-specific adaptation. The CA technologies are essentially herbicide-intensive, machine-intensive, and knowledge-intensive. It, therefore, requires expertise and resources for wide adoption. Policy makers, researchers, and farmers. must adopt a different perspective in order for adoption to be more widespread. Tremendous efforts will be needed to convince farmers to adopt Conservation Agriculture, specifically in dry regions. It is particularly encouraging that the CA Global Community at the 8th World Congress on Conservation Agriculture set a notional goal of transforming 50% of the global cropland area into CA by 2050.

KEY PRINCIPLES OF CONSERVATION AGRICULTURE

Core practices of conservation agriculture (CA) activate a range of interlinked physical, chemical, biological, and hydrological processes that help revive and sustain the health and functionality of soil systems (Anderson, 2015). CA along with complementary agricultural strategies- like integrated management of crops, soils, nutrients, water, pests, energy, labour, and farm machinery to enhanced productivity, improved ecosystem services, and higher efficiency and sustainability across various land-based agricultural systems.

The following ecological improvements are made possible by key principles of conservation agriculture: they are regenerative, increase the potential for land productivity, and allow any modern or modified traditional genotype to operate at its best phenotypically.

- **Continuous no or minimum mechanical soil disturbance**. Sowing of plants directly into untilled soil and zero-till weeding using herbicides preserves soil organic matter; promotes soil biological processes; improves soil structure and porosity and overall soil health; and enhance productivity, system efficiency, resilience, and ecosystem services.

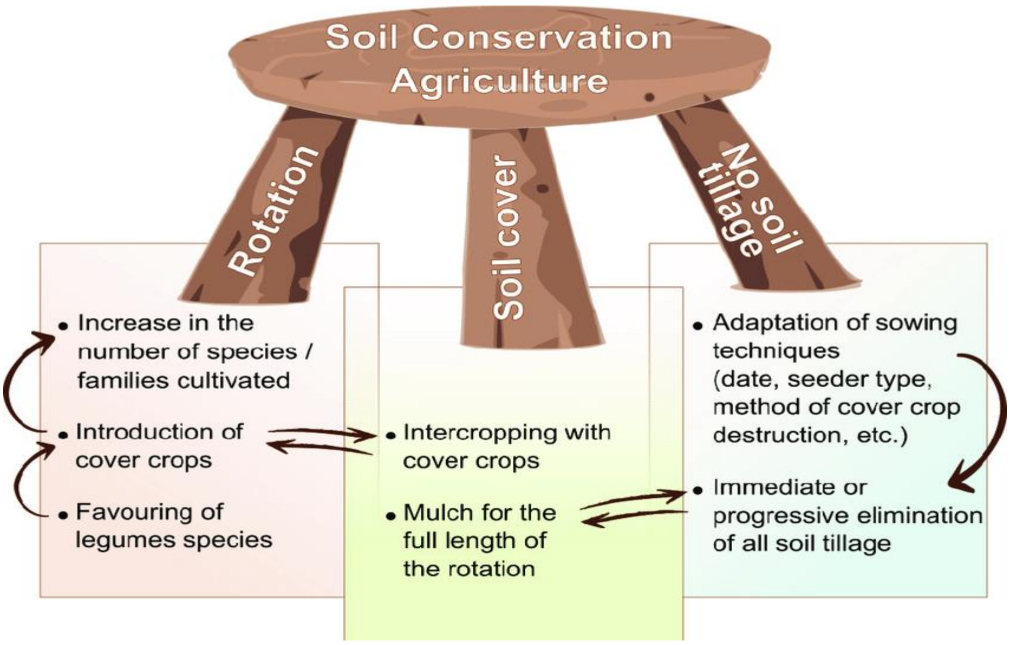

Fig: Components of Conservation Agriculture (Chabert, A. (2018).

- **Permanent maintenance of biomass mulch soil cover.** Crop residues, such as stubble, and cover crops are retained on the soil surface for soil conservation; increasing soils ability to store water and nutrients; incorporation of organic matter and carbon into the soil improving soil's microbial activity and enhanced soil health, enhances soil structure; help in integrated weed, pest, and nutrient management; and boost ecosystem services, productivity, system efficiency, and resilience (Farooq *et al*., 2022).
- **Diversification of crop species**. Crop diversification like crop rotations, associations, and sequential cropping with maintains soil's fertility and nutrient balance is adopted. This helps in soil organic matter buildup and increasing system productivity, efficiency and sustainability. Crops may be annuals, perennials like trees, nitrogen-fixing legumes, and pasture, as appropriate, including cover crops. Scientific and empirical evidence from around the world supports the earlier contribution.

BENEFITS OF CONSERVATION AGRICULTURE

AGRONOMIC BENEFITS

Adoption of conservation agriculture (CA) significantly improves soil productivity and crop performance. The retention and incorporation of crop residues increase soil organic matter content, initially in the surface layers and gradually in deeper soil horizons. Enhanced organic matter improves fertilizer-use efficiency, soil water-holding capacity, aggregation, and cation exchange capacity, thereby strengthening the physical, chemical, and biological health of soils. Conservation agriculture also improves soil structure through greater aggregate stability and promotes effective soil and water conservation.

ENVIRONMENTAL AND SOIL HEALTH BENEFITS

Conservation agriculture enhances soil microbial activity and biodiversity by increasing organic inputs. Surface residues protect the soil from the impact of raindrops, reducing crust formation, runoff, and erosion while increasing water infiltration. Residue cover also acts as a barrier to wind and water flow, slowing evaporation and conserving soil moisture. Additionally, CA improves air and water quality by minimizing nutrient losses and contributes to climate change mitigation through carbon sequestration (Teng et al., 2024).

CHALLENGES OF CONSERVATION AGRICULTURE

Conservation agriculture is a holistic approach for growing crops which requires an innovative system perspective to deal with diversified, flexible and context specific needs of technology and their management. So, more Research and Development will require for various distinctive features to address the challenge. Among them are:

(a) **Understanding The System** Conservation agricultural is more complicated as compared with conventional system. The primary barrier to the CA system's widespread adoption has been site-specific knowledge. It will be extremely difficult to manage these systems effectively in terms of understanding the fundamental procedures and component interactions that drive the overall system performance. For example, surface-maintained crop residues act as mulch and so reduce soil water losses through evaporation and maintain a moderate soil temperature. However, at the same time crop leftovers represent an easily decomposable supply of organic matter and could harbour undesired pest populations or affect the system ecology in some other way. No-tillage systems will affect the root system's distribution and penetration depth, which will affect the uptake of nutrients and water as well as the cycling of minerals.

Therefore, it is necessary to acknowledge conservation agriculture as a system and create management plans (Bhan & Behera, 2014).

(B**) Building A System and Farming System Perspective**– A system viewpoint is established working in conjunction with farmers. A core group of scientists, farmers, extension workers and other stakeholders working in partnership mode will therefore be important in developing and promoting innovative technologies. This differs slightly from traditional agricultural R&D in that resources are allocated and research goals are determined within a framework, with minimal focus on establishing connections and forming alliances with partners in related disciplines.

(C) **Technological Challenges**– Although the fundamental ideas of conservation agriculture, such as surface managed crop wastes and no tillage, are widely known, the main obstacle is implementing these techniques in different farming contexts. These issues include the creation, standardization, and uptake of agricultural equipment for minimally disturbing the soil during planting, as well as the advancement of crop harvesting and management systems.

(D) **Site Specificity**– Although conservation agriculture system adaptation will be very site specific, learning from different sites will be a valuable approach to understand why some technologies or practices work well in one set of circumstances but not in others. Building a knowledge base for sustainable resource management will be accelerated by this learning approach.

SUSTAINABLE SOLUTIONS

In order to support and sustain the spread and widest benefit sharing from the application of all rainfed and irrigated CA systems, the science that supports the CA paradigm must be established as a regular part of the concern for managing a dynamic and innovative knowledge system that can help to generate new knowledge, new technologies, and new enabling social and institutional arrangements. This must involve the immediate restructuring of both public and private research, education, and development organizations toward the acceptance and dissemination CA.

- It is important to recognize the harm that both traditional and modern tillage-based agriculture have produced around the planet. It is necessary to stop and reverse the rate of land deterioration and abandonment in order to restore them using the CA's principles.
- The agriculture industry as a whole has tremendous prospects to use CA-based agricultural land and landscape management to provide its entire spectrum of ecosystem services, including providing, regulating, supporting, and cultural. It is the duty and responsibility of farmers, land managers, the

food and agricultural service sectors, policymakers, and supporting institutions to minimize or prevent the degradation of agro-ecosystems and ecosystem services and to restore them to their ecologically desirable state.

- Subsidy-based agricultural development tactics must be discontinued in favour of incentive-based agricultural growth. Farmers should receive recognition and incentives for implementing CA systems and practices that benefit society through ecosystem services.
- The creation of national CA associations must be encouraged in order to support and create farmer-driven procedures for CA adoption and dissemination, as well as to get and draw in the institutional support needed to sustain an innovative and competitive CA-based food and agriculture industry.
- In order to monitor CA adoption, its impact on agriculture and rural development, and to encourage the mainstreaming of CA on farms and in all auxiliary public, private, and civil sectors, multi-stakeholder national platforms for CA development and dissemination in the Asia-Pacific region must be established.

CONCLUSION

Conservation agriculture (CA) represents a key pathway toward sustainable agricultural development by promoting efficient resource use and long-term ecosystem health. Its benefits operate across multiple scales: at the nano- and field level, CA improves soil structure, organic matter, and biological activity; at the micro-level, it reduces input use, lowers production costs, and enhances farm profitability; and at the macro-level, it contributes to poverty reduction, food security, and climate change mitigation. Realizing these benefits at scale requires coordinated global action involving international institutions such as the World Bank and the Food and Agriculture Organization of the United Nations. The establishment of supportive legislation at national and regional levels is essential, followed by integration into a global CA platform. Additionally, increased international funding is needed to strengthen research, extension, and awareness, particularly among smallholder farmers in tropical regions. By reducing resource degradation, lowering cultivation costs, and improving efficiency, conservation agriculture can drive productive, competitive, and environmentally sustainable farming systems. “Conserving resources while enhancing productivity” should therefore guide future agricultural policy and practice.

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NEXT-GENERATION FODDER SYSTEMS FOR ENHANCED NUTRITIONAL SECURITY

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ABSTRACT

India's rapidly expanding livestock sector faces a critical fodder shortage due to declining land availability, climate variability, soil degradation, and inconsistent feed quality. Ensuring year-round access to nutritious fodder requires a transition from conventional practices to next-generation production systems. Climate-resilient innovations such as hydroponic and vertical fodder cultivation, along with non-conventional feed resources like Azolla, Opuntia, and Spirulina, offer promising solutions. These approaches enhance productivity, water-use efficiency, and nutrient density while reducing land requirements. Additionally, perennial fodder grasses and improved fodder preservation techniques support sustained fodder availability, strengthening livestock productivity, smallholder resilience, and national fodder security.

KEYWORDS: Innovation, Smart farming, Soil less cultivation, Sustainable agriculture

INTRODUCTION

India has the largest livestock population in the world, with 536.76 million animals. As an agrarian nation, India's economy is mostly based on agriculture and related industries, of which raising livestock is a crucial component that accounts for around 5% of the nation's GDP. Being the largest milk producer, the monetary value of milk produced far exceeds the combined worth of rice and wheat, and is a good protein source for the vegetarian population (Vaghamashi et al., 2022). However, the disappointing paradox is that India's milk productivity is so low (4.87 kg per cow), that it lags far behind the global average productivity (7.2 kg per cow). This low production is caused by a number of causes, including inadequate feed management and nutrition etc. In India, 89.4% of farmers are small and marginal, who struggle with a shortage of land and high-quality feed (Dhamodharan et al., 2024). Due to urbanisation and unplanned expansion of agriculture, arable land is declining and adequate grazing lands are absent so farmers rely heavily on dry fodder. Although fodder is an essential component for animals, farmers typically prioritize producing high-value crops on the limited areas. Currently we are facing a deficit of 35.6% green fodder (Singh et al., 2022) resulting in suboptimal feeding practices and inconsistent quality.

For quality milk production, livestock should be fed with well-moist, nutrient-rich and fibre-rich fodder, and these characteristics pertain to green fresh fodder round the year.

Climate change exacerbates these issues by affecting cattle productivity both directly and indirectly. Direct effects are heat stress and indirectly by disrupting fodder availability and quality. The uneven, undistributed rainfalls and temperature hikes makes the crop production unpredictable leading to several crop failures. Moreover the CO_2 concentration has exceeded 426 ppm (Sharma et al., 2025). The elevation in CO_2 concentration has caused the most effect as it has increased the carbon nitrogen ratio thus decreasing plant's nutritional quality. Additionally, input-intensive agriculture brought about by the green revolution has deteriorated the quality of the soil and water. Soil's physical, chemical and biological degradation resulted in poor agronomic production. As the land will decline further and soil fertility has attained saturation. So, in order to produce year-round quality fodder under changing climatic conditions with minimal resources, it is burning need for the nation to adopt alternative fodder sources. Many climates smart novel fodder producing and preserving techniques are emerging like hydroponic fodder production, vertical farming, non-conventional fodder sources (Azolla, Cactus and spirulina), perennial fodder grasses and technology advancements in fodder preservation. This could help in offering superior quality fodder for the future with reduced dependence on costly concentrates and support sustainable livestock system, therefore making a next generation fodder system.

HYDROPONIC FODDER PRODUCTION

The term hydroponics was derived from Greek word '*hydro*' means water and '*ponos*' means labour. Hydroponics is a novel method, in which plants are grown without soil in a nutrient rich media in controlled environmental conditions like optimized temperature and humidity. Fodder refers to crop that are grown and harvested directly for the purpose of feeding animals. Therefore, hydroponic fodder is the fodder grown without soil in nutrient rich medium. This method provides highly nutritious fodder in very short time span of 8-10 days. It contains vertically stacked plastic or metal trays on which a layer of pre-soaked seeds is spread, and kept moist through drip or spray irrigation. Tray has holes for draining out excess water (Dhamodharan et al., 2024).

After 24 hrs seeds start to germinate, and a 6-8inch high mat of lush green, super tender grass is formed over it in just 7 to 8 days, which is taken out as whole and fed fresh to animals. Left behind tray do not have any kind of residue thus it is a minimal waste generating method. This method eliminates the soil related vagaries like poor fertility, salinity, diseases and pest related to soil.

Moreover, it helps to utilize scarce resources and help in mitigating climate change challenges. The plants here grow faster and can be grown in higher density i.e. 1/5th of overall space is needed and uses 20 times less water than soil based culture (Silberbush et al., 2001). With limited land requirement, this technique provide fodder round the year even in drought prone areas with no risk of failure and providing fast growing green fodder. As claimed by many organizations feeding hydroponically grown green nutrition rich fodder will enhance the animal productivity, fertility and overall health.

1. VERTICAL FARMING FOR FODDER PRODUCTION

The arable land is limited, which is mainly devoted for cereals and cash crop production, giving least privilege to fodder production. As further horizontal expansion of land is negligible, vertical expansion should be done to cope up with fodder scarcity. Vertical farming is the specific practice of growing crops in vertically stacked layers by using 1/10th of land. The fodder is grown here in controlled environmental condition (CEA), where factors such as light, temperature, humidity and carbon dioxide are optimised to provide best growing conditions to plants. This vertical farming help in growing high quality fodder in urban and peri-urban areas with least transportation cost and negligible requirement of storage warehouses. A vertical farming techniques- GIGGINS FARM VILLA (Growables in irrigated grow bags, goats integrated for nutritional security with fowl, azolla, rabbit management vertically and intensively in limited land available) was developed by KVK, Kannur with the goal of integration of agriculture, animal husbandry, and dairy farming (Kishore et al., 2023).

2. NON-CONVENTIONAL FODDER SOURCES

2.1 Azolla-based fodder production

Azolla is an aquatic floating fern scientifically known as *Azolla pinnata* commonly called as duck weed and belongs to family Salviniaceae. It grows naturally in drains, ponds, canals and rivers, on water stagnation. It is triangular in shape and grows in symbiosis with Blue Green Algae (*Anabaena azollae*). Azolla is a promising plant having good nutritive value and easy to cultivate with low cost of production. Azolla contains around 23-27% crude protein and 10% carbohydrates on a dry weight basis (Kathirvelan et al., 2015). Azolla is highly digestible due to its low lignin content and protein rich feed source serving as a protein supplement. It has vital amino acids, vitamins, minerals and growth promotors. Feeding azolla as fodder to animals has resulted in higher milk fat and 7-13% higher milk yield in dairy cows (Kumar et al., 2020).

The ideal pH range is 6.5–7.5, and the growth rate rises with longer photoperiod and temperatures as high as 30°C. The colonizing form absorbs heavy metals from the wastewater and develops the fastest, doubling in as little as five days. It gets ready in 21 days and harvested at regular intervals, but growth slows down in winter thus should be harvested at 30 days interval. The fresh yield is 200-250 g m^{-2} day^{-1} (Pathak et al., 2016).

Table 1: Nutritional content of different *Azolla* species (Kathirvelan et al., 2015)

Nutritional content	*A. caroliniana*	*A. pinnata*
Crude protein (%)	23.07	17.59
Crude Fibre (%)	13.19	16.54
Calcium (%)	2.07	1.67
Phosphorus (%)	0.59	0.46
Iron (%)	0.269	0.231
Zinc (%)	64.51	46.77
Moisture (%)	5	5

It has low input cost and within short period large quantity of fodder is produced. Due to these, azolla can be a good feed source for livestock. However, in India it is only cultivated in southern part. Slow adaptation is due to poor yield, pest handling and storage difficulties and labour difficulties.

2.2 Cactus (Opuntia sp.)

In water scarce regions, forage supply round the year is unreliable and the availability also varies from year to year. The cactus *Opuntia ficus-indica* (L.) of Cactaceae family, can be a good fodder alternative, as it can grow in dry regions with low investment and has higher production than most of the crops grown there. Its above ground part is its stem which are flat oval and known as cladode. These cladodes remain green and succulent throughout the year and are used as forage. It contains average 85- 90% water, along with this it contains 3-7% carbohydrates, 1-2% fibre and 0.5-1% protein. It serves as an excellent energy source, as its 61.7% part is made up of non-fibrous carbohydrates (Ginestra et al., 2009).

It has both spiny and non-spiny types and both have similar feeding values, but spiny type can pose physical damage to animal's alimentary canal. Thus, spines should be removed by scraping or by burning before feeding. Due to high moisture and low protein content, it is better to feed opuntia along with some fibre and nitrogen rich sources to supplement protein requirement. It is highly drought tolerant with high carrying capacity, as well as high water use efficiency. Therefore, making it most suitable fodder option in changing climate, under arid and semi-arid regions (Pathak et al., 2016).

3.3 Spirulina as a fodder supplement

Spirulina (*Arthrospira platensis*), a single celled blue green alga is potential next generation fodder because of its remarkable nutrient density and quick biomass synthesis, it is becoming more and more important as a feed supplement. Previously marketed as a human nutraceutical, it is currently being investigated more and more as a useful cattle feed. Unlike conventional feed sources that mainly supplies bulk, spirulina functions as a nutrient enhancer, containing about 60-70% high quality protein, essential amino acids, vitamins, minerals such as iron and calcium, and powerful antioxidants like carotenoids and phycocyanin.

As reported by many researchers, spirulina supplementation in small quantity, has enhanced milk production, milk fat content, feed efficiency, immune response,, and growth performance in animals (Holman & Malau-Aduli, 2013). It requires a little water and land for growing, also able to grow on non-arable land, and has high productivity per unit area.

3. PERENNIAL CLIMATE RESILIENT FODDER GRASS

They are emerging as one of the most reliable source to eliminate persistent shortage of fodder in India. Perennial fodder once established provides fodder for several years, offering continuous green biomass with lower recurring costs. Perennial fodder forms the backbone of country amid challenges like water scarcity, shrinking arable land, and climate variability and bridges the lean period. Key perennial fodder crops are hybrid Napier (*Pennisetum purpureum* x *P. glaucum*), Guinea grass (*Megathyrsus maximus*) and Buffel grass (*Cenchrus ciliaris*).

a) *Bajra-Napier Hybrid:* Napier being the king of fodder grasses, gives 250-350 t ha^{-1} yr^{-1} of protein rich fodder, containing 8-12% crude protein content. It is ideal for green feeding, silage making and chaffing. Major constraint was no seed production and lack of quality rooted slips for planting. For which a technique has been developed, by wrapping the cuttings in a cloth or paper material and keeping it at

25°C and 80% humidity. These cutting are further used to form rooted slips and also long distance transportation is made easy (Vijay et al., 2018).

b) *Guinea grass* (*Megathyrsus maximus*) - It is highly digestible and palatable with high leaf-stem ratio. It is well adopted by farmers because of its multi cut nature and provides 80-100 t ha^{-1} green fodder yield.

Table 2: Comparative nutritive value of different perennial forage grasses

Nutritive value (DM basis)	Napier-bajra hybrid	Guinea grass	Buffel grass
Crude protein	10.2%	7.5%	6.11-13.6%
Crude fibre	30.5%	30.3%	40.2%
Acid Detergent Fibre (ADF)	40.5-50.2%	29.15%	37.3-49%
Neutral Detergent Fibre (NDF)	74-78%	60.21%	64-74.9%
Ether extract	2.1%	4.9%	2.1%
Calcium	0.5%	2.4%	2.6%
Phosphorus	0.4%	0.19%	1.7%

(Kumar et al., 2023)

c) *Buffel Grass* (*Cenchrus ciliaris*): In arid region and semiarid regions, fodder scarcity could be diminished by planting drought tolerant buffel grass, which provides fodder during lean period. These grasses can also be planted in grass legume system, where nitrogen requirement of the system is fulfilled by biological N-fixation up to some extent. Due to rich source of carbohydrate, these serve as an excellent raw material for silage making.

4. ADVANCE TECHNIQUE FOR FODDER PRESERVATIONS

Fodder conservation is key component of sustainable livestock production, enabling surplus green fodder to be stored safely and used during lean periods. Traditional preservation such as hay making and ensiling have evolved significantly through innovation in technology and mechanization. These techniques ensure better quality by biochemical enhancements, reduce losses and optimize nutrient concentration in fodder.

4.1 *Silage:* Silage is made by preserving green fodder at high moisture content by fermentation of crop at 65% moisture content. Silage preservation depends on controlled anaerobic fermentation of freshly harvested forage. Due to fermentation soluble carbohydrates changes into organic acids, mainly lactic acid, which rapidly declines the pH to inhibit spoiling of forage. This biochemical conversion preserves nutrients and due to its less dependence on weather, makes it superior to dry hay. The major preservative is sodium metabisulphite, which checks bacterial growth and help in partial sterilization. Adding salt in silage makes its more palatable and also helps in fermentation. Some specific lactic acid bacteria (LAB) inoculants are used as bio-preservatives to enhance the fermentation process. They lower down the pH rapidly, suppress undesirable microbes and improve aerobic stability. Thus, improving nutrient preservation and silage stability.

Some fermentation stimulants like molasses and grain cereals, provide additional control over the process and suppress spoilage organism like yeast and moulds. These additives can improve livestock performance, milk production and better rumen health. Based on study conducted by Ishrath and Thomas (2018), the high quality silage can be developed by hybrid Napier harvested at 45 day interval by adding 2% urea + 1% jaggery as additives.

4.2 *Haylage and Balage:* Haylage is low moisture silage (40-60%) or dry silage. It is prepared by combining partial drying with airtight wrapping to promote anaerobic fermentation in haylage, forage is wilted to a mid-range moisture content and then baled and sealed. This process has less storage losses, low weather associated risks and devoid of foul odour. Haylage made up of multispecies are more balanced and nutritious.

Balage, on the other hand are “round bale silage”, which is baled at high moisture content and thereafter, sealed in plastic wrap to avoid spoilage. It is used as a stock fodder, in lean periods. These bales can be made rapidly through balers, where a liquid additive applicator is also fitted. This machinery advancement has made high quality balage economically feasible and transportable.

4.3 *Dehydrated products:* Dried fodder products such as pellets, and cubes represent important modernization in forage preservation, especially where fodder is scarce. Through dehydration, storage life of the fodder is increased and ease of transport is there, while reducing bulky fresh fodder without major loss in nutritive value. The forage is harvested and dried artificially and them made dense for storage by compressing it into wafers, cubes or rolled into pellets. Pellets and cubes are most common dehydrated products. Along with this dehydrated Moringa (*Moringa oleifera*) leaves are very successful in nutritious pellet making.

FUTURE RECOMMENDATIONS

Future strategies must concentrate on integrating climate-smart fodder production with advanced preservation systems in order to provide sustained fodder security while accounting for limited land resources and climatic variability. Subsidies, training, and demonstration facilities should be used to encourage the wider use of hydroponics and vertical farming. Strengthening research-extension links should be prioritized in order to maximize resource utilization, lower production costs, and standardize processes. It is necessary to mainstream non-conventional fodder resources through value addition, ration inclusion, and region-specific farming models. To guarantee a steady supply of biomass, seed development and distribution of stress-tolerant fodder species and high-yielding perennial grasses should be given top priority. Simultaneously, in order to reduce nutrient losses, improved preservation methods require mechanization support and farmer-friendly technologies.

CONCLUSION

Next-generation fodder systems offer a practical, scientific pathway to overcome persistent fodder scarcity, declining resource base, and climate uncertainties. Technologies like hydroponics and vertical fodder production systems enable high productivity under limited resources, while non-conventional sources serve as highly nutritive supplement to fodder in adverse climatic conditions. To bridge the limiting fodder in lean period perennial grasses like napier, guinea grass, and cenchrus serve as nutritive fodder sources, with high biomass supply throughout the year. Together they make a sustainable livestock feeding system with minimal cost and high nutritional security. However, their meaningful impact will depend on farmer awareness, accessibility of these technologies, supportive policies, and adaptation specific to regions. By integrating technological advances with demonstration and implementation, India can move towards resilient, efficient and secure fodder ecosystem.

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PEARL MILLET: A CLIMATE-RESILIENT CROP FOR FOOD AND NUTRITIONAL SECURITY

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ABSTRACT

Pearl millet (Pennisetum glaucum), commonly known as bajra, is a nutritionally rich and climate-resilient cereal widely cultivated in arid and semi-arid regions. Its exceptional tolerance to drought, heat, and poor soils makes it a lifeline crop under changing climatic conditions. Rich in dietary fiber, essential amino acids, iron, zinc, and B-complex vitamins, pearl millet contributes significantly to food and nutritional security. With expanding climate risks and resource constraints, pearl millet offers sustainable solutions for resilient farming systems, livelihood security, and diversified food systems, particularly in developing countries.

KEYWORDS: Climate resilience, food security, nutritional security, pearl millet, sustainable agriculture

INTRODUCTION

Pearl millet (*Pennisetum glaucum* [L.] R. Br.), popularly known as bajra, is one of the oldest cultivated cereal crops and a staple food for millions of people inhabiting arid and semi-arid regions of the world. It is a highly cross-pollinated diploid species (2n = 2x = 14) with an estimated genome size of approximately 1.79 Gb (Varshney et al., 2017). The crop is characterized by exceptional tolerance to drought, high temperature, salinity, and low soil fertility, making it uniquely suited to marginal environments where other cereals fail to perform.

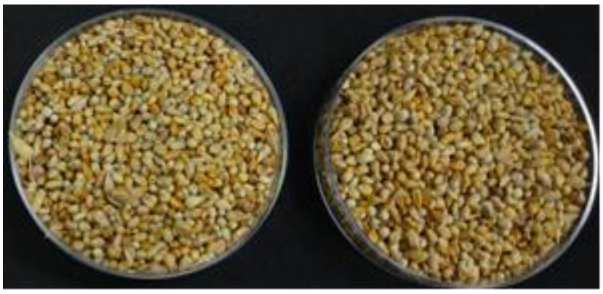
Pearl millet plays a critical role in global food security, particularly under the current scenario of climate variability and increasing frequency of extreme weather events. The crop possesses a deep and extensive root system that allows efficient extraction of soil moisture, enabling survival and grain production under severe water scarcity. Owing to its resilience and adaptability, pearl millet is considered a lifeline crop for resource-poor farmers in dryland ecosystems.

Globally, pearl millet is cultivated in more than 30 countries across Asia, Africa, the Americas, and Australia. India is the largest producer, contributing nearly 44% of global pearl millet production (FAO, 2016). The crop ranks fourth among cereal crops in India after rice, wheat, and maize. Major pearl millet-producing states include Rajasthan, Maharashtra, Uttar Pradesh, Gujarat, and Haryana, together accounting for about 90% of national production.

AGRO-CLIMATIC ADAPTABILITY AND CLIMATE RESILIENCE

Pearl millet exhibits remarkable adaptability to harsh agro-climatic conditions, including high temperatures exceeding 42°C, low and erratic rainfall, and nutrient-poor soils. Its short growth duration, rapid early vigor, and efficient photosynthetic system enable the crop to escape terminal drought stress. Compared to other cereals, pearl millet shows superior water-use efficiency and maintains productivity under limited irrigation or rainfed conditions.

The crop's resilience is further supported by its tolerance to soil salinity and acidity, making it suitable for cultivation in degraded and marginal lands. Pearl millet's genetic diversity provides a valuable resource for breeding climate-smart cultivars capable of withstanding abiotic stresses such as drought, heat, and emerging pest and disease pressures under climate change scenarios.



Pearl millet grain

Field view of Pearl millet

NUTRITIONAL AND HEALTH BENEFITS

Pearl millet is widely recognized as a "nutri-cereal" due to its superior nutritional profile and its role in diversifying diets. The grain is rich in complex carbohydrates, dietary fiber, and high-quality protein containing essential amino acids such as methionine and cysteine, which are limited in other cereals. Whole pearl millet grain has a higher energy content than most cereals, except maize.

Pearl millet is an excellent source of micronutrients, particularly iron and zinc, offering a cost-effective dietary intervention to combat micronutrient deficiencies such as anemia and zinc deficiency prevalent in developing countries. It also contains significant amounts of B-complex vitamins, including niacin, riboflavin, and thiamine, which support metabolic and neurological health.

Due to its low glycemic index and high fiber content, pearl millet is recommended for individuals with diabetes, obesity, and cardiovascular disorders. Regular consumption has been associated with improved digestive health, better glucose regulation, and reduced risk of lifestyle-related diseases.

PEARL MILLET IN FOOD SYSTEMS AND CULINARY USES

Pearl millet is traditionally consumed in various forms such as flatbreads, porridges, fermented foods, and beverages across India and Africa. With increasing consumer awareness and policy support for millets, pearl millet is being incorporated into value-added products such as breakfast cereals, bakery items, snacks, and ready-to-eat foods.

The revival of millets under national and international initiatives has enhanced the market potential of pearl millet-based foods, creating opportunities for entrepreneurship, food processing industries, and nutritional interventions such as school feeding and public distribution systems.

ROLE IN LIVESTOCK FEED AND FARMING SYSTEMS

Beyond human nutrition, pearl millet serves as an excellent fodder crop due to its high biomass production, palatability, and nutritional quality (Daduwal et al., 2024). It contributes significantly to livestock productivity, especially in mixed crop–livestock farming systems prevalent in arid regions.

Pearl millet straw is widely used as dry fodder, while green fodder supports dairy and small ruminant production. Additionally, the crop residues are used for thatching, insulation, and rural housing, thereby enhancing its multifunctional value in farming systems.

INDUSTRIAL AND BIOENERGY POTENTIAL

Pearl millet is gaining attention as a potential bioenergy crop due to its high biomass yield and ability to grow on marginal lands without competing with food crops. It offers opportunities for bioethanol production, biogas generation, and renewable energy development in dryland regions.

The crop's adaptability and low input requirements make it suitable for integrated food–feed–fuel systems, contributing to sustainable rural livelihoods and energy security.

ADVANCES IN GENETIC IMPROVEMENT AND BIOTECHNOLOGY

The availability of the pearl millet genome sequence has accelerated molecular breeding and genomics-assisted crop improvement (Varshney et al., 2017). Modern breeding approaches, including marker-assisted selection, genomic selection, and gene discovery, are being employed to improve yield stability, nutritional quality, and stress tolerance.

Biofortification efforts focusing on iron and zinc enhancement have shown promising results, aligning pearl millet improvement programs with global nutrition and health goals.

CHALLENGES AND FUTURE PROSPECTS

Despite its advantages, pearl millet faces challenges such as low productivity in traditional systems, limited market integration, susceptibility to certain diseases, and declining consumer preference. Strengthening seed systems, improving value chains, promoting mechanization, and enhancing awareness about nutritional benefits are essential to unlock the full potential of the crop.

Future research should focus on developing climate-resilient, high-yielding, and nutritionally enriched varieties, supported by enabling policies and investments to mainstream pearl millet in sustainable food systems.

CONCLUSION

Pearl millet stands out as a climate-resilient and nutritionally superior cereal with immense potential to address food, nutrition, and livelihood security under changing climatic conditions. Its adaptability to drought, heat, and poor soils makes it a strategic crop for sustainable agriculture in arid and semi-arid regions. Rich in dietary fiber, essential amino acids, and micronutrients, pearl millet contributes significantly to combating malnutrition and lifestyle-related diseases. Beyond food, its value as fodder, industrial raw material, and bioenergy resource enhances farming system sustainability. Strengthening research, breeding, value addition, and policy support will be crucial to mainstream pearl millet as a key component of climate-smart and nutrition-sensitive agricultural systems.

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