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True Agriculture
Volume 1, Issue 1, July 2026, pp 01-03

CONTENTS

True Agriculture
Volume 1, Issue 1, July 2026, pp 01-03

Livestock in Agriculture: Foundation of Resilient and Sustainable Farming Systems

Naresh Kumar and Javana Rame

1. Introduction

Livestock production is deeply integrated into agricultural systems, particularly in developing economies where farming is characterized by small landholdings and mixed farming practices. Beyond its direct contribution to food production, livestock acts as a stabilizing component in agricultural systems by diversifying income sources and reducing vulnerability to climatic and economic shocks.

In India, the livestock sector has shown consistent growth and contributes significantly to agricultural GDP. For smallholder farmers, animals such as cattle, buffalo, goats, and sheep function not only as productive assets but also as financial security. The multifunctional nature of livestock—providing food, manure, draft power, and income—makes it indispensable for sustainable rural development.

2. Livestock in Integrated Farming Systems

Integrated farming systems combine crop production with livestock rearing to optimize resource use and improve overall farm efficiency. In such systems, outputs from one component serve as inputs for another, creating a circular flow of resources.

For example:

- Crop residues are used as animal feed
- Animal manure is applied to fields as organic fertilizer
- Livestock supports traction in traditional farming systems

This integration enhances nutrient recycling, reduces dependence on external inputs, and improves soil health over time. It also minimizes waste and increases overall farm productivity.

3. Economic Contribution and Income Stability

Livestock contributes to rural economies through both direct and indirect channels. Milk production, meat processing, egg production, and wool harvesting generate continuous

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income streams. Unlike seasonal crops, livestock products can be marketed throughout the year, ensuring steady cash flow.

In addition, livestock serves as a form of financial asset that can be liquidated in times of need. This role is particularly important in regions where access to formal credit is limited. Farmers often rely on livestock as a means of coping with unexpected expenses or crop failures.

4. Employment Generation and Social Impact

The livestock sector provides employment across various stages of production and value chains. Activities such as feeding, breeding, healthcare, transportation, and marketing create job opportunities for rural populations.

Women play a significant role in livestock management, particularly in tasks such as milking, feeding, and care of animals. This involvement contributes to women's economic empowerment and enhances household decision-making capacity.

5. Nutritional Security and Human Health

Animal-derived foods are essential for balanced nutrition as they provide high-quality proteins, essential amino acids, vitamins, and minerals. Milk, eggs, and meat are particularly important in addressing protein-energy malnutrition and micronutrient deficiencies.

The availability of livestock products improves dietary diversity and contributes to better health outcomes, especially among children and vulnerable populations.

6. Environmental Role and Sustainability

Livestock plays a dual role in environmental sustainability. On one hand, it contributes to nutrient cycling and soil fertility through manure application. On the other hand, it can have environmental impacts if not managed properly.

Sustainable livestock practices include:

- Efficient feed management
- Proper manure handling
- Integration with crop systems
- Use of improved breeds

When managed effectively, livestock systems can enhance ecological balance and contribute to climate-resilient agriculture.

7. Challenges in Livestock Sector

Despite its importance, the livestock sector faces several challenges:

- Shortage of quality fodder
- Disease outbreaks and inadequate veterinary services

- Low productivity of indigenous breeds
- Limited access to markets and infrastructure

Addressing these challenges requires coordinated efforts in research, extension services, and policy support.

8. Future Prospects

Advancements in breeding, nutrition, and health management offer opportunities to improve livestock productivity. Digital technologies, precision farming, and data-driven decision-making can further enhance efficiency.

The integration of livestock with climate-smart agriculture practices will play a crucial role in ensuring long-term sustainability.

9. Conclusion

Livestock is not merely an auxiliary component of agriculture but a central pillar of sustainable farming systems. Its contribution to income generation, nutritional security, and environmental sustainability makes it indispensable for rural development. Strengthening the livestock sector through innovation and policy support will be key to achieving resilient agricultural systems.

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True Agriculture
Volume 1, Issue 1, July 2026, pp 04-07

Artificial Intelligence in Agriculture: Revolutionizing Farming for a Sustainable Future

Subhash Yadav and Manoj Kumar

Introduction

Agriculture has always been the backbone of human civilization, providing food, fiber, fuel, and livelihoods to billions of people worldwide. However, modern agriculture faces unprecedented challenges, including climate change, declining soil fertility, water scarcity, increasing pest and disease outbreaks, labor shortages, and the growing demand for nutritious food from a rapidly expanding global population. Traditional farming methods, while valuable, are often insufficient to address these complex issues efficiently.

Artificial Intelligence (AI) has emerged as a transformative technology capable of reshaping agricultural systems by enabling data-driven decision-making, improving productivity, optimizing resource utilization, and enhancing environmental sustainability. AI integrates advanced technologies such as machine learning, computer vision, robotics, remote sensing, and predictive analytics to support farmers throughout the agricultural production cycle. From crop planning and precision irrigation to disease detection, livestock monitoring, and market forecasting, AI offers innovative solutions that improve efficiency while minimizing production costs and environmental impacts. Despite its immense potential, the widespread adoption of AI in agriculture faces challenges such as limited digital infrastructure, affordability, data privacy concerns, inadequate technical expertise, and policy constraints.

1. Understanding Artificial Intelligence in Agriculture

Artificial Intelligence refers to computer systems capable of performing tasks that normally require human intelligence. These tasks include learning from experience, recognizing images, understanding language, solving problems, identifying patterns, and making informed decisions.

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Rather than replacing farmers, AI functions as an intelligent assistant that processes large volumes of information and provides timely recommendations.

Modern AI systems continuously improve their performance as they receive more data. This ability allows agricultural models to become increasingly accurate in predicting crop yields, identifying diseases, estimating irrigation requirements, and forecasting market prices. The integration of AI into agriculture supports precision management by recognizing the variability that exists within fields instead of treating entire farms uniformly.

Several core technologies form the foundation of AI-driven agriculture.

Machine Learning enables computers to learn from historical agricultural data without explicit programming. Machine learning models identify relationships among weather conditions, soil characteristics, crop growth, pest outbreaks, and production outcomes. As additional data become available, prediction accuracy improves over time.

Computer Vision allows computers to interpret visual information obtained through digital cameras, drones, smartphones, and satellites. Images can be analyzed to detect nutrient deficiencies, identify weeds, estimate crop growth stages, monitor fruit maturity, and diagnose plant diseases with remarkable speed and consistency.

Deep Learning, a specialized branch of machine learning, uses artificial neural networks inspired by the human brain. These models excel in analyzing complex agricultural images and identifying subtle differences that may not be easily recognized by the human eye.

Natural Language Processing (NLP) enables communication between humans and machines using ordinary language. AI-powered agricultural advisory systems can answer farmers' questions, translate technical recommendations into local languages, and provide voice-based support through smartphones.

Predictive Analytics combines historical records with current environmental data to forecast future events. Farmers can receive early warnings regarding drought, frost, disease outbreaks, insect infestations, or market fluctuations, enabling proactive management decisions.

Agricultural Robotics represents another rapidly advancing area of AI. Autonomous robots equipped with cameras, sensors, and intelligent navigation systems perform tasks such as planting, spraying, harvesting, pruning, and weed removal with high precision. These machines reduce dependence on manual labor while improving operational efficiency.

Together, these technologies create intelligent agricultural ecosystems where information flows continuously from the field to digital platforms, supporting evidence-based management decisions throughout the production cycle.

2. AI Applications in Crop Production

Artificial intelligence is transforming crop production by enabling farmers to make precise, timely, and informed decisions throughout the cropping season. Traditional farming often relies on generalized recommendations based on regional averages, whereas AI facilitates field-specific management by analyzing real-time data collected from multiple sources. This shift from conventional to data-driven agriculture enhances productivity while reducing production costs and environmental impacts.

Modern AI systems integrate information from weather stations, soil sensors, satellite imagery, drones, mobile applications, and farm machinery. These technologies continuously monitor crop growth and environmental conditions, allowing farmers to identify potential problems before they become severe. As a result, agricultural inputs such as seeds, fertilizers, pesticides, and water can be applied more efficiently, leading to higher yields and improved resource conservation.

2.1 Precision Agriculture

Precision agriculture is one of the most significant applications of artificial intelligence in modern farming. It focuses on managing field variability by applying the right input, at the right place, at the right time, and in the right quantity. Rather than treating an entire field uniformly, AI identifies differences in soil fertility, moisture levels, crop vigor, and pest incidence across different locations.

Machine learning algorithms analyze historical crop performance, soil characteristics, weather conditions, and satellite data to generate detailed management recommendations. Farmers can develop variable-rate application maps for fertilizers, irrigation, and crop protection chemicals. These recommendations improve nutrient use efficiency, reduce wastage, lower production costs, and minimize environmental pollution caused by excessive chemical application.

2.2 Smart Irrigation Management

Water scarcity has become one of the most critical challenges facing global agriculture. Efficient irrigation management is therefore essential for sustainable crop production. Artificial intelligence significantly improves irrigation scheduling by continuously monitoring soil moisture, weather forecasts, evapotranspiration rates, and crop growth stages.

2.3 Intelligent Pest Monitoring

Insect pests remain one of the major constraints to agricultural productivity. Conventional pest monitoring methods often require frequent field visits and manual observations, making them labor-intensive and time-consuming. AI offers more efficient alternatives by automating pest surveillance and outbreak prediction.

Smart insect traps equipped with cameras and image recognition software can identify insect species, estimate population density, and transmit data directly to cloud-based monitoring platforms. Machine learning models combine pest observations with weather conditions, crop growth stages, and historical outbreak records to forecast pest infestations before they reach economically damaging levels.

2.4 Yield Prediction and Harvest Optimization

Accurate yield estimation plays a crucial role in farm planning, storage management, transportation, marketing, and food supply chain operations. Artificial intelligence improves yield prediction by integrating information from multiple sources including weather records, satellite imagery, crop growth models, soil fertility data, irrigation schedules, and management practices.

Machine learning algorithms continuously update predictions throughout the growing season as new field data become available. Farmers can estimate production well before harvest and make informed decisions regarding labor requirements, storage facilities, marketing strategies, and contractual agreements.

3. Conclusion

Artificial Intelligence has emerged as one of the most influential technological innovations shaping the future of agriculture. By combining advanced data analytics, machine learning, computer vision, robotics, and digital communication technologies, AI enables farmers to make informed decisions throughout the agricultural production cycle. From precision crop management and intelligent irrigation to livestock monitoring, disease diagnosis, market forecasting, and climate risk assessment, AI enhances agricultural productivity while promoting efficient resource utilization.

The adoption of AI contributes not only to increased farm profitability but also to environmental sustainability through optimized use of water, fertilizers, pesticides, and energy. These improvements support global efforts to achieve sustainable food systems capable of feeding a growing population under changing climatic conditions.

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True Agriculture
Volume 1, Issue 1, July 2026, pp 08-10

Dragon Fruit Cultivation: A High-Value Crop for Climate-Resilient Agriculture

Deen Dayal Sharama and Chita Meena

Introduction

Dragon fruit (*Hylocereus* spp.), commonly referred to as pitaya, has gained considerable attention in recent years due to its high economic returns, nutritional benefits, and adaptability to diverse agro-climatic conditions. In the context of changing climate patterns, declining water resources, and the need for crop diversification, dragon fruit cultivation presents a promising opportunity for farmers.

Unlike many conventional fruit crops, dragon fruit requires relatively less water and can tolerate adverse environmental conditions. This makes it particularly suitable for arid and semi-arid regions such as Rajasthan, Gujarat, and parts of Maharashtra. The crop is also gaining importance in peri-urban agriculture due to its high market demand and export potential. The increasing consumer preference for nutritionally rich and visually appealing fruits has further boosted its demand in both domestic and international markets. As a result, dragon fruit cultivation is being promoted as a viable option for enhancing farmer income and ensuring agricultural sustainability.

2. Botanical and Physiological Characteristics

Dragon fruit belongs to the family *Cactaceae*, which is characterized by succulent plants adapted to dry environments. The plant exhibits a climbing growth habit and requires external support for proper development.

2.1 Morphology

The plant consists of fleshy, triangular stems that store water, enabling it to survive under drought conditions. The presence of aerial roots allows the plant to attach to supporting structures.

2.2 Flowering Behavior

Dragon fruit produces large, white, fragrant flowers that bloom at night, typically opening in the evening and closing by morning. This unique characteristic necessitates effective pollination during a short time window.

2.3 Pollination

Pollination plays a crucial role in fruit set. While some varieties are self-pollinating, others

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require cross- pollination. In commercial cultivation, manual pollination is often practiced to improve fruit size, uniformity, and yield.

3.1 Climate, Temperature and Soil Requirements

Dragon fruit thrives in warm and humid climates but can tolerate a wide range of environmental conditions. Optimal growth occurs between 20°C and 35°C. Extreme cold or frost conditions can damage plant tissues.

3.2 Rainfall and Soil

Moderate rainfall is suitable; however, excessive rainfall and waterlogging can adversely affect root health. Well-drained sandy loam soils with good organic matter content are ideal. Soil pH between 5.5 and 7.0 is considered suitable for optimal growth.

4. Propagation and Planting Techniques

4.1 Propagation

Dragon fruit is primarily propagated through vegetative methods using stem cuttings. This ensures genetic uniformity and faster establishment compared to seed propagation.

4.2 Planting System

Plants are usually grown on vertical support structures such as concrete poles with a circular frame at the top. This system facilitates better canopy development and ease of harvesting.

4.3 Spacing

Proper spacing (2–3 meters between plants) ensures adequate sunlight penetration and air circulation, reducing the risk of diseases.

5. Crop Management Practices

5.1 Training and Pruning

Regular pruning is essential to remove excess vegetative growth and promote fruiting. Training the plant on support structures helps in efficient utilization of space.

5.2 Irrigation Management

Although drought-tolerant, dragon fruit responds well to irrigation during flowering and fruiting stages. Drip irrigation is commonly used to optimize water use efficiency.

5.3 Nutrient Management

Application of organic manure along with balanced doses of nitrogen, phosphorus, and potassium enhances plant growth and fruit quality. Micronutrients also play a role in improving yield.

6. Pest and Disease Management

Dragon fruit is relatively resistant to pests and diseases; however, some common issues include:

- Stem rot

- Fruit rot
- Mealybugs

Proper field sanitation, drainage, and timely application of control measures help in minimizing losses.

7. Harvesting and Post-Harvest Management

Fruits are ready for harvest approximately 25–35 days after flowering. Maturity is indicated by a change in skin color from green to bright red or pink.

Post-harvest handling includes:

- Careful harvesting to avoid damage
- Sorting and grading
- Proper packaging for transport

8. Yield and Economic Analysis

Dragon fruit cultivation is highly profitable due to its premium market value. Yield varies depending on management practices but generally ranges between 10–30 tonnes per hectare.

9. Challenges and Future Scope

Despite its advantages, challenges include:

- Limited availability of quality planting material
- Lack of technical knowledge
- Market fluctuations

Future scope lies in:

- Development of improved varieties
- Expansion of processing industries
- Export promotion

10. Conclusion

Dragon fruit cultivation offers a sustainable and profitable alternative for farmers seeking diversification. Its resilience to environmental stress, combined with high market demand, makes it a suitable crop for modern agriculture. With proper management and institutional support, it can significantly contribute to income generation and agricultural sustainability.

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True Agriculture
Volume 1, Issue 1, July 2026, pp 11-17

Mulching in Vegetable Production: Enhancing Productivity and Resource Efficiency

Sunita Choudhary

Introduction

Mulching is a widely recognized agronomic practice that involves covering the soil surface with various materials to create a favorable microenvironment for plant growth. In vegetable production systems, where crops are highly sensitive to fluctuations in soil moisture, temperature, and nutrient availability, mulching plays a crucial role in stabilizing these factors and improving overall crop performance.

Vegetable crops typically have shallow root systems and high water requirements, making them more vulnerable to moisture stress and temperature extremes compared to field crops. Under such conditions, mulching acts as a protective layer that reduces environmental stress and enhances resource use efficiency.

Black plastic mulch is widely used for its high efficiency in weed control and water conservation, though it is costly and can leave harmful residues. in contrast, grass mulch is cheaper and eco-friendly but less durable. Biodegradable mulches, made from starch-based polymers, offer a promising alternative to plastic.

Mulching is becoming essential in modern agriculture due to water scarcity, resource degradation, and the need for chemical-free weed and pest control. it reduces evaporation by blocking sunlight, maintains soil moisture, lowers soil temperature, and promotes better plant growth and survival. it also enhances water infiltration and nutrient availability while minimizing weed competition (Easmin et al., 2009; Khan et al., 2015). In summary, mulching is a sustainable, low-cost technique crucial for improving yield and quality in high-value vegetable crops, particularly under changing climatic conditions.

Intentions for Covering Holes

Tree coverings are used for a variety of reasons but water conservation and erosion control are the most important objectives of their agricultural use in arid areas. Other reasons for the use of topsoil cover include soil temperature adjustment, soil conservation, nutrient supplementation, soil structure improvement, weed control and crop quality control.

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Benefits: Soil moisture retention: Covering with mulching prevents evaporation of excess moisture. it reduces soil compaction and helps to ensure soil penetration, prevents excessive flow and checks for soil erosion.

- Soil temperature control.
- Control weeds growth.
- Reduce soil erosion.
- Prevent leaching of fertilizer.
- Reduce winter damage by reducing temperature fluctuations, lowering water. loss of plants and a decrease in the crown of plants and roots.
- Reduce fruit rot by removing contact between the fruit and the soil.
- Provides a conductive environment for plant growth.
- improve seed germination.
- Premature maturation.

Barriers to covering a hole

- Covering tree seedlings is a lot of work.
- inorganic holes are expensive.
- Warm humidity allows the spread of disease and pests.
- The use of polythene mulch creates a wet anaerobic state that leads to root death.
- Slow-growing plants are suppressed.
- Holes in dry trees sometimes pose a risk of fire.

Types of mulching holes

- Holes in Organic trees
- Holes in inanimate(inorganic) trees

Organic tree holes:

The incorporation of a layer of plant and animal fossils to protect the soil and provide a good environment for plant growth. Natural mulches rot over time and return nutrients to the soil. Organic holes, such as leaves, compost, grass or sawdust (Kayum et al. 2008).

Types of Organic Mulches

A. **Paper cover:** Crushed and parchment paper is used. Apply two to three layers of paper at a time and cover with organic material such as a leaf cover or pieces of grass to hold them tight.
B. **Vegetation cover with dry leaf seedlings:** Leaves work best when dropped before being applied as a cover for tree seedlings. it is easily available and inexpensive. Example: Sugarcane

leaves or bananas and other leaves.

C. **Sawdust mulch:** it can decompose quickly and combine on its own but requires high nitrogen to decompose. Sawdust is used after treatment against termites.

D. **Grass and grass cover tree seedlings:** ideal for winter protection. if used in the summer, be sure to add extra nitrogen to the soil. Example: paddy straw.

E. **Manure / compost cover:** These cover material is placed in a layer of 2 - 3 ”layers on top of the plants or soil and is used for good looks. Compost needs to rot well before laying; otherwise it can damage the plants. in addition, covering these materials will improve soil fertility by increasing the state of organic carbon.

Inorganic tree coverings:

inorganic tree coverings are often used to create weed boundaries. inorganic mulch, such as rocks or stones and plastic fi lms do not rot easily. These are also used for decorative purposes

Inorganic Mulch species

Basically, there are two types of mulch in terms of material used. They are as follows:

A. **Plastic holes:** By carefully choosing the shape of the plastic cover as a color and thickness, it is possible to control the surrounding soil surface.

- Black plastic mulch: Black plastic film does not allow sunlight to pass through the soil. Thus, photosynthesis does not occur in soil where there is no sunlight under a dark film. Black plastic mulch helps retain moisture and control weed growth. However, it may increase soil temperature. it gives harvest in advance for 7-14 days. it also helps to increase yields especially for leafy vegetables (Ashrafuzzaman et al. 2011).
- Clear and transparent plastic mulch: Let the sunlight pass and the weeds grow, however, by using a herbicide cover on the inner side, weed growth can be observed. it is very effective as a soil-based solarization film to reduce soil-borne diseases and other weeds. This is an application for raising children by heating the beds before sowing the seeds to grow a nursery, which provides 100% seed germination and disease-free kindergarten. Transparent films work in hilly areas to increase soil temperature in cold winter weather.
- Two-color plastic mulch: Also known as wavelength selective / photo selective film is designed to absorb certain wavelengths of the sun's rays, which change the spectrum of sunlight passing through a film or return to plant skin. it has had a significant effect on plant growth and development. The effects are warming of the soil temperature and suppressing weed growth. Examples:

1. Yellow / Black: Attract certain insects and trap them, which protect them from disease.
2. White / Black: Reduce soil temperature.
3. Silver / black: Expels aphids and trips.
4. Red / black mulch: Slow rotation that allows the rays to pass & warm soil but also exposes the rays behind the plant bed changes the ratio of R: FR light, which leads to plant changes, flower growth and nutrient fluctuations in early infection and proliferation. Veza. This mulch is mainly used in tomato plants.

Perforated tree holes:

Impaired mulch: Mulch contains elements of iron and copper that break down after exposure to light and degrade very slowly. These flower buds break under ultraviolet light.

Bio-degradable mulch: it disperses under natural conditions and is mixed into the soil after cover time. Mulches are made from a combination of starch and decaying plastic.

Aluminum foil or Aluminum painted mulch: This light mulch under the leaves may repel aphids and thrips. When vector insects are repelled, germ transmission also decreases.

Rock mulch:

Widely used in home garden and kitchen. The stones do not retain moisture but retain heat in the soil.

installation of mulch film

Tractor plastering equipment is designed and operational.

Selection of mulch films

The choice of film color depends on the specific objective to be achieved such as weed control, soil temperature or cooling or disease control or improved plant growth etc. A film with a diameter of 90 cm & 120 cm is widely used.

Mulch Size:

The size of the mulch should be commensurate with the type and age of the crop

Table: 1 Mulch size should be used for vegetable crops

S.No.	Mulch material	Thickness of mulching
1	Compost	3-4 inches
2	Green leaves	3-4 inches
3	Dry leaves	6 inches
4	Grass clipping	2-3 inches
5	Paper	3-4 sheets
6	Onion /Garlic scale	2-3 inches
7	Plastic mulch	
8	Annuals- Short duration crop	20-25 micron
9	Biennial- Medium duration crop	25-50 micron
10	Perennial- Long duration crop	50-100 micron

impact of mulching on crop production and soil health

- **Soil Temperature:** Mulching regulates soil temperature by affecting radiation balance and moisture evaporation. Organic residues act as insulators, stabilizing root zone temperatures and protecting young seedlings (Parmar et al., 2013).

- **Germination and Growth:** Some organic mulches may release phytotoxic substances that affect seed germination and plant growth. However, grass mulches have shown better outcomes in promoting early vegetation.

- **Plant Microclimate:** Mulching improves the microclimate by reducing soil water evaporation and moderating root zone temperature. While moderate temperature rise encourages root growth, excessive heat—especially under plastic mulch—can hinder root development.

- **Soil Fertility:** Plastic mulches, especially black polyethylene, reduce nutrient loss and help retain soil moisture, preserving essential nutrients like Mg and Ca. Studies show improved tomato yields and reduced nitrate leaching under mulched conditions.

- **Soil Biological Properties:** Mulching enhances microbial activity by maintaining moisture and moderate temperature. Organic mulches also promote higher earthworm populations—up to **155% more** than in bare soil (Mahmood et al., 2002).

- **Soil Structure:** Organic mulches contribute to increased soil organic carbon, improving soil aggregate stability and overall structure.

- **Groundwater Conservation:** Mulching significantly reduces irrigation needs—by **20–46%**—through better moisture retention. Plastic mulches also improve water-use efficiency in crops like tomatoes.

- **Crop Growth and Yield:** Black polyethylene mulch supports **early and higher yields**, notably in crops like **muskmelon**, by optimizing soil conditions and minimizing stress during early growth stages.

Conclusion:

Organic farming is more than just avoiding chemical fertilizers and pesticides—it's a holistic approach focused on maintaining soil fertility and managing pests naturally. This system emphasizes building healthy soil through the use of organic matter and minimal tillage. Organic residues are left to decompose in the field, and weeds are controlled through mulching and natural suppression. Mulching plays a vital role in organic farming by reducing soil erosion, retaining moisture, suppressing weeds, regulating temperature, and gradually releasing nutrients. The use of black polythene mulch has significantly improved the growth and yield of various vegetable crops.

in conclusion, mulching is a beneficial and cost-effective practice for vegetable farmers. it enhances productivity and fruit quality, making it a practical strategy for sustainable and high-yielding organic agriculture.

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True Agriculture
Volume 1, Issue 1, July 2065, pp 18-23

Innovative Technologies for Enhancing Water Productivity

Ashok Kumar

Introduction

Water is a vital component of plant life, comprising approximately 90% of cytoplasm, 35–95% of leaf tissue, 60–90% of root tissue, and 70–90% of fleshy fruits. It plays a critical role in plant physiology, acting as a nutrient carrier, facilitating photosynthesis, and supporting thermoregulation, which is essential for plant growth and survival.

Water scarcity is a major limiting factor in crop production, exacerbated by climate change and increasing competition for resources. Since agriculture is the largest consumer of freshwater (blue water footprint), efficient irrigation practices must prioritize maximizing yield per unit of water used rather than just per unit of land.

With india's population projected to reach 1.4 billion by 2025, the demand for food, fiber, feed, and fuel is growing rapidly. To meet this demand, india must produce 380 million tonnes of food grains annually, despite having only 2.3% of the world's land and 4% of its freshwater resources. Per capita arable land and water availability are shrinking—from 0.34 ha (1950-51) to a projected 0.08 ha (2025), and from 5300 m^3 (1951) to under 1500 m^3 (2025)—below the global threshold for water stress.

Therefore, water productivity (WP), defined as crop output per unit of water used (Molden, 2010), has become a critical concept. Promoted through slogans like "More Crop per Drop" or "Per Drop More Crop," improving WP is essential for sustainable agriculture in water-scarce regions like india.

Types of Water productivity:

a) Physical water productivity is defined as the ratio of agricultural output to the amount of water consumed from all available sources including irrigation, rainfall etc. (kg of produce per cubic metre of water consumed (through evapo-transpiration) during crop growth, kg/m^3).

b) irrigation water productivity is defined as ratio of the crop output to the irrigation water applied by the farmer/ irrigation system either through surface canals, tank, pond or the well and tube

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well during the crop growth. Thus irrigation is an economic activity and the farmer has to incur certain expenditure to apply the water (kg/m^3).

c) Economic water productivity is defined as the ratio of value of crop output to the amount of water consumed or to the amount of irrigation water applied by the farmer (expressed as Rs /m^3).

Factors affecting WP:

The factors which affect or influence crop yield (numerator of the productivity equation), and water applied or need to be applied (denominator of the same equation), obviously influence the water productivity.

The factors are:

A. Crop Cultivar Type

- Stomatal behavior influences how efficiently plants use water during CO_2 uptake.
- C_4 plants (e.g., maize, sorghum) generally exhibit higher WP than C_3 plants (e.g., wheat, rice).
- in C_3 plants, genotypes with lower carbon isotope discrimination tend to have better WP due to efficient internal CO_2 concentration regulation.

B. Applied Water & irrigation Practices

- Techniques like partial root-zone irrigation, deficit irrigation, and drip systems enhance WP by optimizing water use (Ali et al., 1997).
- Trade-off: Slight reduction in yield for improved WP.
- During drought stress, pre-anthesis stem reserves (sugars, starch) play a crucial role in maintaining grain filling and final yield.

C. Soil Factors

- Soil texture and organic matter influence water retention and release.
- Soils that dry quickly reduce osmotic adjustment and affect plant growth and WP.
- Nitrogen nutrition promotes early leaf development, affecting water use and evaporation.
- Organic matter also supports beneficial microbial activity.

D. Agronomic Practices

- Timely sowing, even plant establishment, optimal fertilization, and adequate plant population significantly affect WP.
- Early canopy development helps reduce soil evaporation and weed competition.
- Mulching and stubble management improve soil water balance, reduce runoff, and increase infiltration.
- Sowing winter crops early (in warm soils) improves canopy cover and reduces evaporative losses.

E. Climate Change

- Rising CO_2 levels, fluctuating temperature, and precipitation changes alter crop water use.
- in some regions, shortened growing periods may decrease yield and WP.
- High water-holding soils may buffer negative climate impacts.
- Expanded irrigation can increase yields but may compromise environmental quality.

F. Economic Factors

- improving WP often requires investment in irrigation infrastructure (drip, sprinkler systems), which includes high fixed and operational costs.
- in developing countries, these costs may be prohibitive.
- Farmers choose cropping patterns based on profitability per unit of land or water, responding to market dynamics and resource availability.

Technologies for enhancing water productivity.

1. **Genetics**
2. **irrigation methods**
    - micro sprinkler
    - drip irrigation
    - deficit irrigation : RDi and PRD
3. **Management practices**
    - seed priming
    - seedling age
    - choice of crop
    - sowing method (use lesser land leveler)
    - Nutrient management

- weed management

4. **Mulches and anti-transparent**
5. **Water harvesting**
6. **Crop Genetics**

Genetic approaches to improving water use efficiency (WUE) focus on selecting crop varieties with traits such as tolerance to heat, cold, salinity, pests, and drought, as well as shorter growing seasons, earlier flowering, and better nutrient use efficiency, suited to specific regional conditions. Crop breeding is most effective when it aligns growth cycles and harvest times with local rainfall patterns at key growth stages. Efforts also target reducing the base water requirement for yield, especially in dryland crops. However, due to genetic-environmental interactions, genetic gains alone may not dramatically improve WUE. instead, combining these advances with efficient cultural and management practices is more likely to deliver substantial and immediate benefits in reducing water use.

7. **irrigation methods**

Efficient water use is vital, especially in arid and semi-arid regions. Traditional surface irrigation methods like check basin lead to significant water losses through seepage, evaporation, and nutrient leaching. in contrast, drip irrigation applies water slowly and directly to the root zone, wetting only 15–60% of the soil surface and minimizing losses (Rao et al., 2016). This method enhances crop survival, yield, and quality while saving 18–42% water and improving irrigation water use efficiency (iWUE) by 35–75%. Drip irrigation, a key tool in precision farming, is now widely used for both wide- and close-space crops. Paired row planting further reduces system costs and water use without affecting plant population.

8. **Anti-transparent and mulches**

Anti-transpirants, once explored in the 1960s–70s, reduce water loss by closing stomata or reflecting sunlight. They can lower evapotranspiration by **5–10%** for about **two weeks**, but often hinder photosynthesis more than water loss. Due to limited effectiveness and short duration, they are not widely practical for large-scale farming.

9. **Conservation Agriculture**

Conservation agriculture will increase the water productivity through reduce tillage, mulches, selection of crop and cropping systems. Zero tillage conserving soil moisture by leaving old root holes to facilitate internal drainage, averts the pulverization of soil aggregates and formation of pans, reduces draft power for planting and gives shelter, winter food and nesting sites for fauna. Crop residues on the surface practically eliminate wind and water erosion, reduce soil moisture loss through the mulch effect, slow spring warm-up.

Mulches conserve water through reduce evaporation losses from soil surface, maintain soil temperature, check weed growth improve the efficiency of irrigation.

10. Water harvesting

in the dry areas water not land is the most limiting resources for improved agricultural production maximizing WP and not yield per unit of land, is therefore a better strategy for dry farming system. Under such conditions more efficient water management techniques must be adopted. Supplement irrigation is a highly efficient agricultural production and improving livelihoods in the dry rainfed area. in dry areas most of rainwater is lost by ET. Therefore, the rainwater productivity is extremely low. Water Harvesting can improve agriculture by directing and concentrating rainwater through runoff to the plant and other beneficial use. it was found that over 50 % of lost water can be recovered at a very little cost.

Conclusion:

We need to concentrate much regarding higher production, higher quality production with the use of limited water. After gone through the literature and seeing the day-by-day reduction of fresh water it can be concluded that water productivity is a basic need of agriculture.it can be concluded that different improved irrigation tech. agronomic management practices and conservation agriculture increase water productivity.

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Bio-Fertilizers an Eco-friendly Technology for Environmental Sustainability Present Status and Future Prospects in india

Sumit Yadav

Introduction

The agriculture sector contributes a significant portion to the global GDP, but increasing population, estimated to reach 9.5 billion by 2050, along with challenges like declining fertile land, urbanization, climate change, and nutrient deficiencies, threatens future food security. Modern high-input farming systems rely heavily on synthetic fertilizers to meet crop nutrient demands, yet only 30–40% of these nutrients are utilized by plants, with the rest causing environmental pollution, eutrophication, and health hazards due to heavy metals and nitrates.

This calls for sustainable alternatives, and biofertilizers—beneficial microbes like *Rhizobium*, *Azotobacter*, and blue-green algae—have emerged as eco-friendly solutions. These microbes promote plant growth by nitrogen fixation, solubilizing phosphorus and potassium, producing phytohormones, enhancing nutrient availability, and improving resistance to stress. For example, *Rhizobium* benefits legumes, *Azotobacter* suits cereals like wheat and maize, while *Anabaena* with water fern can contribute up to 60 kg N/ha in rice fields. Though not a complete replacement for chemical fertilizers, biofertilizers play a vital role in integrated nutrient management (iNM), offering a cost-effective and environmentally sustainable way to enhance soil health and agricultural productivity.

Types of bio fertilizers

Bio fertilizers are the formulation of living or latent cells of microbes, which provides additional advantage in nutrient uptake and plant performance in rhizosphere. The biofertilizer formulation technique is simple with low installation cost and the former can be composed of single or a mix of two or more diverse microbial strains including Acetobacter, Azotobacter, Bacillus, Pseudomonas, Rhizobium, PGPB or plant growth promoting bacteria and AM or arbuscular mycorrhiza (Basu et al., 2021; Fausi et al., 2021; Mohanty et al., 2021). Biofertilizers are subdivided into different groups (Fig. 1)

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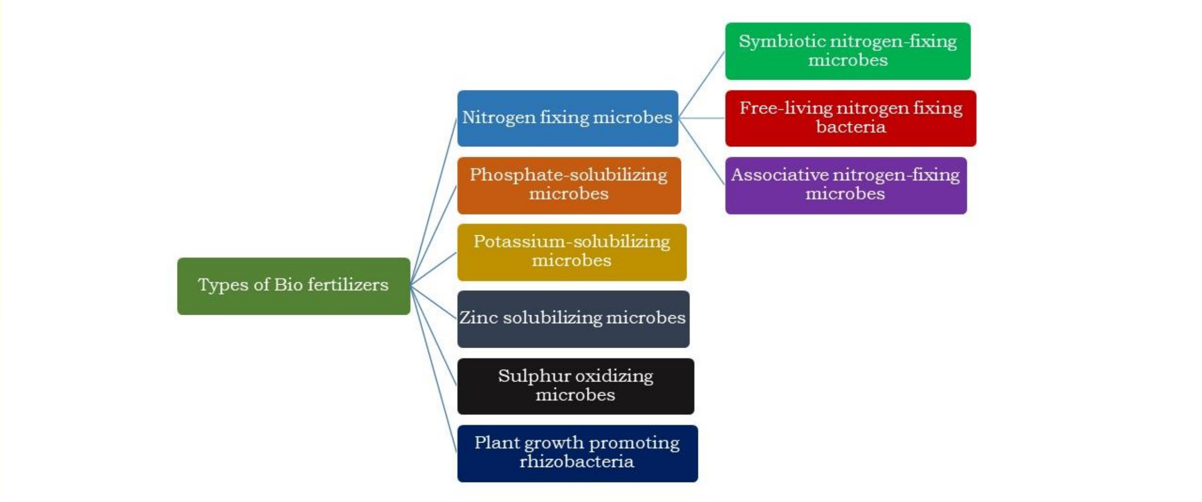

Fig.1. schematic presentation of types of biofertilizers.

which are as follows:

- **Nitrogen-fixing microbes**

Biological nitrogen fixation (BNF) is the process by which diazotrophic microbes convert atmospheric nitrogen (N_2) into ammonia, supporting crop growth sustainably without the environmental damage caused by chemical fertilizers (e.g., nitrogen oxide emissions, eutrophication, and soil acidification). BNF is mainly performed by certain bacteria and archaea, including groups like green sulphur bacteria, firmibacteria, actinomycetes, cyanobacteria, and proteobacteria. Methanogens are the only nitrogen-fixing archaea. These microbes have varied physiologies—some are aerobic (*Azotobacter*), anaerobic (*Clostridium*), facultatively anaerobic (*Klebsiella*), phototrophic (*Anabaena*, *Rhodobacter*), or chemolithotrophic (*Leptospirillum ferrooxidans*). Diazotrophs inhabit soil and water and can contribute between 20–300 kg N/ha/year. They form associations with grasses, legumes (via root nodules), woody plants, termites, and cyanobacteria. The enzyme nitrogenase plays a central role in converting nitrogen gas to ammonia during fixation.

- **Symbiotic nitrogen-fixing microbes**

Symbiotic nitrogen-fixing microbes, especially those belonging to the *Rhizobium* group (including *Mesorhizobium*, *Azorhizobium*, *Allorhizobium*, *Sinorhizobium*, and *Rhizobium* spp.), establish symbiotic associations with the roots of leguminous plants, forming specialized structures called root nodules. These nodules host nitrogenase, an oxygen-sensitive enzyme responsible for converting atmospheric nitrogen (N_2) into ammonia (NH_3), thereby enhancing plant nitrogen availability (Sindhu & Dadarwal, 1997; Marchal & Vanderleyden, 2000). The presence of leghemoglobin in nodules helps maintain low oxygen levels required for nitrogenase activity. This biological nitrogen fixation significantly reduces the need for synthetic nitrogen fertilizers in legumes, compared to non-leguminous crops (Goyal et al., 2021). inoculation with efficient *Rhizobium* strains has demonstrated substantial increases in plant biomass and grain yield across various legume crops (Sindhu et al., 1992; Thies et al., 1991; Goel et al., 2001). Additionally, residual soil nitrogen after legume harvest often equals 30–80 kg N/ha, further improving soil fertility (Sindhu et al., 1992). Apart from *Rhizobium*, *Azolla-Anabaena azollae* symbiosis is another highly effective nitrogen-fixing system. *Anabaena*, a blue-green alga found in rice fields, can fix 40–60 kg N/ha and enrich the soil with organic matter, making it an important biofertilizer in lowland paddy cultivation (Kannaiyan, 1993). Despite proven benefits, field-level inconsistencies in *Rhizobium* performance have also been reported (Miller & May, 1991), indicating the need for strain specificity and favorable environmental conditions.

B. Free-living nitrogen fixing bacteria

Azotobacter is one of the most prominent free-living diazotrophic bacteria commonly found in the rhizosphere of non-leguminous crops like wheat, rice, cotton, and vegetables (Sindhu & Lakshminarayana, 1982; Jain et al., 2021). Species such as *A. chroococcum*, *A. vinelandii*, and others can fix about 2–18 mg of nitrogen per gram of carbon used in culture (Moraditochaee et al., 2014). Some strains also exhibit biocontrol activity and secrete bioactive compounds like phytohormones, enhancing root growth and nutrient uptake (Mahanty et al., 2016). *A. vinelandii* produces azotobactin siderophores under iron-deficient conditions (Noar & Bruno-Bárcena, 2018). Wang et al. (2018) observed a 158% increase in nitrogenase activity when *A. chroococcum* was supplemented with a carbon source. These properties make *Azotobacter* an effective and eco-friendly biofertilizer in sustainable agriculture.

A. Associative nitrogen-fixing microbes

Azospirillum is a widely used biofertilizer in wetland agriculture across many countries such as italy, USA, Brazil, india, and Pakistan (Okon & Labandera-Gonzalez, 1994; Bashan & De-Bashan, 2010). it associates with plant roots and enhances growth through the production of phytohormones like iAA, gibberellins, and cytokinins. Among the 17 identified species, *Azospirillum brasilense* and *A. lipoferum* are the most studied (Rodrigues et al., 2015). it can fix 20–40 kg nitrogen per hectare annually in non-leguminous crops. *Azospirillum* improves root morphology and helps plants tolerate stress by modulating osmotic balance and cell wall flexibility

(Groppa et al., 2012). Bacilio et al. (2004) found that *A. lipoferum* improved plant growth under salt stress. Co-inoculation with *Rhizobium* and *Azospirillum* significantly boosts nodulation, biomass, and nitrogen fixation compared to *Rhizobium* alone (Molla et al., 2001; Remans et al., 2008). This makes *Azospirillum* a valuable biofertilizer in sustainable and stress-resilient agriculture.

C. Phosphate-solubilizing/mobilizing microbes

Phosphorus is an essential macronutrient for plant growth, but its bioavailability in soil is very limited despite total phosphorus content ranging from 400–1200 mg/kg of soil (Bamagoos et al., 2021). Most phosphorus exists in insoluble forms like tricalcium and dicalcium phosphate, which are not readily available to plants (Miller et al., 2010; Wang et al., 2017). Phosphate-solubilizing bacteria (PSB) help convert these insoluble forms into plant-available inorganic orthophosphates through solubilization and mineralization processes (Oteino et al., 2015; Tandon et al., 2020). PSBs secrete organic acids such as citric and gluconic acid to solubilize mineral phosphates, and enzymes like phytases and nucleases to mineralize organic phosphate sources (Novo et al., 2018; Ku et al., 2018). in addition, PSBs promote plant growth by producing phytohormones like indole acetic acid (iAA) and siderophores (Hariprasad & Niranjana, 2009). Notably, rhizobacteria that produce higher levels of iAA (>20 µg/mL) show enhanced phosphate-solubilizing capacity, especially when L-tryptophan is added to the growth medium (Alemneh et al., 2021).

D. Potassium-solubilizing microbes

Potassium is ranked at third position as crucial plant nutrient after nitrogen and phosphorous (Ding et al., 2021; Patel et al., 2021). Potassium is available in plentiful amount in the soil but only a small fraction (1–2%) of it is available to plants. Hence, a system of continuous replenishment of potassium in soil solution is needed for its adequate availability to crop plants (Park et al., 2009; Meena et al., 2014; Parmar and Sindhu, 2019). Like other nutrients, potassium also influences growth and development of plants, and if it is not supplied in required amount, plant growth will be slow with poorly developed roots and low yield (Williams and Pittman, 2010). Potassium also affects important physiological processes such as starch production, root growth and stomatal movement (Gallegos-Cedillo et al., 2016). in deficiency of potassium, root growth becomes slow and gets poorly developed, seeds will be of small size and disease susceptibility will be more leading to reduction in crop yield (Troufflard et al., 2010).

E. Zinc solubilizing microbes

Among micronutrients, zinc deficiency is the most widespread nutrient deficiency (Hafeez et al., 2013). Deficiency of zinc (Zn) imparts negative effects not only to plants but also to human health. Deficiency of zinc is ranked at 5th position in terms of human-related death in under developed countries. Zinc is involved in the synthesis of chlorophyll, enzymes, proteins and metabolic reactions (Ali et al., 2008). Plants suffering from zinc deficiency produce symptoms like chlorosis, low membrane integrity and leaf size, retarded shoot growth, reduced grain yield, pollen formation, root development, water uptake and transport and increased vulnerability to heat, light and fungal infections (Tavallali et al., 2010; Kamran et al., 2017). in wheat, Zn deficiency causes stunted growth and yellowing of leaves. Hence, it becomes utmost important to address zinc deficiency as a top priority concern among other micronutrients (Hussain et al., 2018; Kumar et al., 2019).

F. Sulphur oxidizing microbes

Macronutrient sulphur is needed in high amount by plants as it is a constituent of macromolecules like amino acids (cysteine, cystine and methionine) and also involved in regulation of various enzymes like superoxide dismutase, ascorbate peroxidase, monodehydro-ascorbate reductase, dehydro-ascorbate reductase and glutathione reductase. Sulphur deficiency causes chlorosis and low lipid content along with lower plant growth and yield (Saha et al., 2018). Soil is composed of organic as well as inorganic sulphur and the process of conversion of organic sulphur into plant utilizable inorganic sulphur (i.e., SO4 2−) form is carried out by sulphur-oxidizing bacteria (SOB) including Xanthobacter, Alcaligenes, Bacillus, Pseudomonas, Thiobacillus sp., Thiobacillusthioparous and T. thioxidans (Kertesz and Mirleau, 2004; Riaz et al., 2020). Sulphur-oxidizing microorganisms also exhibited other plant growth-promoting activities.

G. Plant growth promoting rhizobacteria

PGPR includes bacteria, which are free living in nature and obtained from the rhizosphere having the capability to produce and secrete metabolites, which promote plant growth after colonizing their roots (Beneduzi et al., 2012). Upon inoculation, PGPR help the plant to withstand drought stress (Timmusk et al., 2014; Niu et al., 2018; ilyas et al., 2020), salinity (Mayak et al., 2004; Bharti et al., 2013) and biotic stress (de Vasconcellos and Cardoso, 2009; Verma et al., 2016). inoculation of PGPRs has been reported to enhance seed germination, soil fertility and plant growth via the production of auxins, ethylene, gibberellins etc. (Jang et al., 2017; Tahir et al., 2017).

Members from various genera like Agrobacterium, Arthrobacter, Alcaligenes, Azotobacter, Acinetobacter, Actinoplanes, Bacillus, Frankia, Pseudomonas, Rhizobium, Micrococcus, Streptomyces, Xanthomonas, Enterobacter, Cellulomonas, Serratia, Flavobacterium, Thiobacillus etc. are included in PGPR (Glick and Gamalaro, 2021; Kumar et al., 2021; Santoyo et al., 2021b).

Mechanisms of action of beneficial microbes

Microbes, due to their phylogenetic diversity and functional versatility, interact with plants through various relationships like symbiosis, parasitism, commensalism, amensalism, and neutralism (Glick & Gamalero, 2021). These plant-associated microbes, collectively known as the plant microbiome, depend on plant photosynthesis for growth and in return promote plant health and development (Wang et al., 2008; Lebeis et al., 2012; Klaus & Bulgarelli, 2015; Zhang et al., 2021). Beneficial microbes in the plant microbiome enhance soil quality, increase nutrient availability, bolster resistance against pathogens, and produce growth-promoting hormones (Chaparro et al., 2012; Wasai & Minamisawa, 2018). Although the soil microbiome consists of diverse organisms—bacteria, fungi, algae, protozoa, archaea, and viruses—bacteria play a key role in promoting sustainable crop productivity (Mueller & Sachs, 2015; Haney et al., 2015). Microbes in the rhizosphere improve plant growth directly by nutrient solubilization and hormone production (Malik & Sindhu, 2011) and indirectly by suppressing pathogens, reducing abiotic stress, and remediating pollutants (Santoyo et al., 2021; Sehrawat et al., 2021). These microbial functions are being increasingly explored for enhancing crop production in an eco-friendly and sustainable manner.

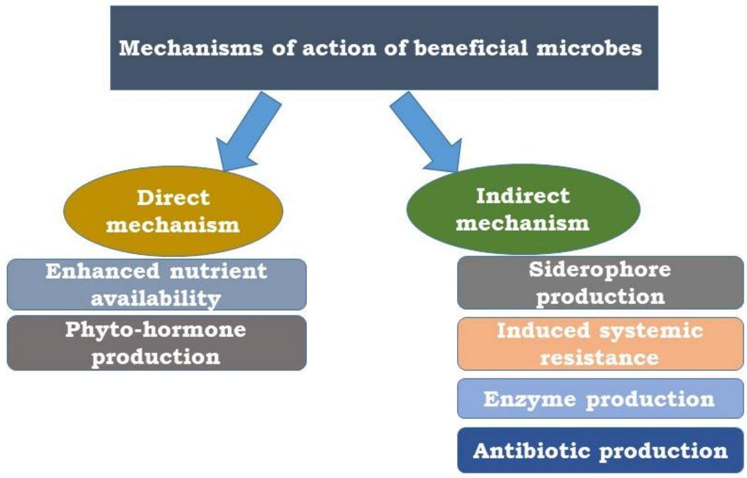

Fig 2. Diagrammatic presentation of Mechanisms of action of beneficial microbes

A. Direct mechanisms involved in plant growth promotion

Beneficial bacterial inoculants provide nitrogen, phosphorous, potassium and other plant nutrients to the crop without any chemical input to soil leading to improvement of plant growth and increase in crop yield (Singh and Gupta, 2018; Tiwari et al., 2018; Vimal et al., 2018; Basu et al., 2021). Moreover, production and excretion of different phytohormones i.e., iAA, gibberellins (GA) and cytokinins have been reported to increase the root surface area for more adsorption of plant nutrients from the soil (Jangu and Sindhu, 2011; Duca et al., 2014; Khan et al., 2016; 2020).

- **Enhanced Nutrient Availability:** Plants require around 16 essential micro- and macro-nutrients for proper growth, and their availability is influenced by soil type, climate, and crop variety. Soil microbes, especially in the rhizosphere, enhance nutrient availability through nitrogen fixation, solubilization of phosphate, potassium, and zinc, and production of phytohormones (Richardson et al., 2009; Sehrawat and Sindhu, 2019). Mycorrhizal fungi and PGPR play a critical role in nutrient mobilization and stress mitigation (Santoyo et al., 2021a). These microbes improve plant metabolism, alter root exudates, and enhance interaction with other soil organisms (Adesemoye and Kloepper, 2009). inoculation with *Azotobacter chroococcum* has shown increased nitrogen and phosphorus uptake in maize, leading to improved growth and yield (Song et al., 2021).
- **Phytohormone production:** Plants and certain beneficial bacteria synthesize phytohormones in minute concentrations that regulate key physiological processes such as root and shoot growth, flowering, senescence, seed development, cell division, gene expression, and stress responses (Jangu & Sindhu, 2011; Khan et al., 2020). These hormones enhance root surface area and root hair length, thereby improving nutrient and water uptake (Tsegaye et al., 2017). in stressful conditions, plant growth-promoting rhizobacteria (PGPR) either produce phytohormones or modulate their levels within the plant, aiding in defense, metabolism, and abiotic stress management (Malik & Sindhu, 2011; Khan et al., 2020). Major phytohormones include auxins, cytokinins, gibberellins, ethylene, and abscisic acid, while other hormones like jasmonates, brassinosteroids, and strigolactones are also involved in stress regulation (Cassań et al., 2014). Most PGPRs are known to produce auxins, cytokinins, and ethylene, but only a few strains can synthesize gibberellins (van Loon, 2007; Egamberdieva et al., 2017; Abd Allah et al., 2018).

B. indirect mechanisms

Plant pathogens such as bacteria, fungi, and viruses significantly reduce global crop yields, causing annual losses of 20–40% in cereals and legumes (Oerke, 2006). Overuse of chemical pesticides for controlling these diseases has led to environmental pollution and health risks. As an eco-friendly alternative, antagonistic microorganisms are being explored as biopesticides to boost crop production (Santoyo et al., 2012; Anand et al., 2020; Jiao et al., 2021; Wang et al., 2022). These microbes promote plant health and suppress pathogens through multiple mechanisms including production of siderophores, hydrolytic enzymes, antibiotics, volatile organic compounds (VOCs), hydrogen cyanide, and by inducing systemic resistance in plants (Sehrawat & Sindhu, 2019; Sharma et al., 2019; Khanna et al., 2021). These biocontrol mechanisms not only reduce disease incidence but also contribute to enhanced plant growth and yield.

I. **Siderophore production:** iron is an essential element for plant metabolism, especially in respiration and photosynthesis, but in aerobic soils, it primarily exists as Fe^{3+}, which is poorly available to plants due to its tendency to form insoluble hydroxides and oxyhydroxides (Zuo & Zhang, 2011; Pahari & Mishra, 2017). Microorganisms secrete low-molecular-weight compounds known as siderophores, which chelate Fe^{3+} and convert it into the more absorbable Fe^{2+} form, thereby enhancing iron uptake by plants (Kashyap et al., 2017; Rasouli-Sadaghiani et al., 2014). These siderophores, rich in electron-donating atoms like oxygen and nitrogen, also help in the acquisition of other micronutrients such as molybdenum and vanadium, especially in nitrogen-fixing microbes like *Azotobacter vinelandii* (McRose et al., 2017).

Siderophores are produced by various beneficial microbes including *Pseudomonas*, *Azotobacter*, *Bacillus*, *Rhizobium*, and *Streptomyces*, contributing to both plant growth and biocontrol (Sahu & Sindhu, 2011; Sultana et al., 2021). Specifically, fluorescent *Pseudomonas* species have been shown to enhance iron nutrition in graminaceous and dicot plants and reduce disease incidence by strengthening structural tissues such as the sclerenchymatous sheath in maize, leading to improved yield and overall plant health (Shirley et al., 2011).

II. **Enzyme production:** Microbial extracellular enzymes regulate metabolic activities by breaking down complex biomolecules, aiding in carbon cycling, bioremediation, and plant growth promotion (Burns et al., 2013). Plant Growth-Promoting Rhizobacteria (PGPR) like *Pseudomonas*, *Bacillus*, *Xanthomonas*, and *Agrobacterium* produce enzymes such as proteases and lipases (Ghodsalavi et al., 2013). Under abiotic stress, antioxidant enzymes including ascorbate peroxidase (APX), catalase (CAT), glutathione peroxidase (GPX), and superoxide dismutase (MnSOD) help in stress mitigation (Willekens et al., 1995; Bharti et al., 2016). Hydrogen peroxide also acts as a signaling molecule in stress and growth processes (Sofo et al., 2015). While these enzymes support plant health, inconsistent results in field conditions are due to complex interactions between plants, microbes, and environmental factors.

III. **Antibiotic production:** Soil harbors a vast diversity of microbes—commensals, pathogens, and symbionts—creating intense competition for nutrients and space (Mendes et al., 2013). To survive, microbes evolve various strategies, with antibiotic production being a common and effective one (Sehrawat and Sindhu, 2019; Jiao et al., 2021). Antibiotics, which are low-molecular-weight toxic compounds, help microbes suppress competitors. They may be volatile (e.g., aldehydes, ketones) or non-volatile (e.g., phenylpyrroles, cyclic lipopeptides) (Gouda et al., 2017). Besides antimicrobial activity, antibiotics can exhibit antiviral, antioxidant, antitumor, and even plant growth-promoting properties when used in low concentrations (Kim, 2012).

IV. **induced systemic resistance:** Plants defend themselves against pathogens using mechanisms like induced Systemic Resistance (iSR) and Systemic Acquired Resistance (SAR), primarily activated through jasmonate and ethylene signaling pathways (Pangesti et al., 2016). iSR is triggered by microbial molecules such as flagellin, chitin, siderophores, and salicylic acid, with biocontrol agents (e.g., *Bacillus*, *Pseudomonas*, *Serratia*) using PAMPs, MAMPs, and elicitor molecules like VOCs and miRNAs to stimulate defense responses (Doornbos et al., 2012; Rodriguez et al., 2019). iSR can enhance resistance in non-host specific ways, as shown in tomato plants treated with *Bacillus amyloliquefaciens* (Beris et al., 2018) and *Pseudomonas aeruginosa* (Kousar et al., 2020). *Serratia marcescens* also induces resistance in cucumber against multiple pathogens via siderophore production (Press et al., 2001). These responses lead to callose and lignin deposition, stress gene expression, enzyme activation (e.g., chitinase, PPO), and phytoalexin production (Heil and Bostock, 2002). For instance, salicylic acid in poplar plants enhances catechin synthesis to suppress foliar pathogens (Ullah et al., 2019b).

Conclusion

The excessive and indiscriminate use of chemical fertilizers, especially phosphorus, has led to nutrient buildup and degradation of soil health, threatening long-term agricultural sustainability. in this context, the development and promotion of efficient biofertilizers offer a viable solution to reduce dependency on synthetic inputs and mitigate environmental pollution. Achieving this requires collaborative, interdisciplinary research involving soil microbiologists, agronomists, plant breeders, and economists. While biofertilizers like *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria, and arbuscular mycorrhizal fungi hold immense promise, their potential remains underutilized.

Strengthening awareness, enhancing production capabilities, supporting startups, and digitizing the supply chain are crucial for scaling biofertilizer adoption. Though initiatives began during the Seventh Five-Year Plan, the current pro-agriculture policy environment presents an ideal opportunity to consolidate efforts for sustainable, eco-friendly farming practices.

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