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ADVANCES IN AGRICULTURE, HORTICULTURE AND ANIMAL HUSBANDRY

VOLUME I

Editors:
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Dr. Narayan Totewad
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PREFACE

Agriculture, horticulture, and animal husbandry form the foundation of human civilization and continue to play a pivotal role in ensuring food security, economic stability, and sustainable development across the globe. In recent decades, these sectors have witnessed rapid advancements driven by scientific research, technological innovation, and evolving socio-economic needs.

This book, "Advances in Agriculture, Horticulture and Animal Husbandry," aims to present a comprehensive overview of recent developments, challenges, and opportunities within these vital disciplines. It brings together contributions from experts, researchers, and practitioners who are at the forefront of innovation and practice in their respective fields.

The chapters cover a wide range of topics including sustainable farming practices, precision agriculture, plant breeding, pest management, modern irrigation techniques, post-harvest technologies, livestock nutrition, genetic improvement, and animal health management. Emphasis has been placed on integrating traditional knowledge with modern scientific approaches to address the pressing issues of climate change, resource conservation, and global food demand.

We hope that this volume will serve as a valuable resource for students, researchers, policymakers, extension workers, and all stakeholders involved in agricultural sciences. By fostering a deeper understanding of current trends and future directions, this book aspires to contribute meaningfully to the advancement and sustainability of agriculture, horticulture, and animal husbandry.

We extend our sincere gratitude to all the authors, reviewers, and contributors whose efforts have made this publication possible. Their dedication and expertise have significantly enriched the content and scope of this work.

- Editors

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EFFECTIVE STRATEGIES FOR RECLAMATION OF SALINE AND ALKALI SOILS

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Abstract:

The soil is the source form which produces our food, clothing and shelter. Our existence depends on soil. Soil is one of the world's most important natural resources. Soil the interface of air, minerals, water and life. Soil (Pedon) occupies a central position in man's environment, the whole of which comprises lithosphere, hydrosphere, atmosphere and biosphere. Every year, soil becomes saline and alkaline by the constant use of chemical fertilizer. These soils are developed in arid and semi-arid regions. Poor drainage, basic fertilizers, parent rock materials etc. are responsible for development of saline and alkaline soils. In saline and alkaline soils, most of the plant nutrients become unavailable and consequently plant growth is affected. The accumulation of salts makes the soil infertile and renders it unfit for agriculture. Physical, Chemical and Biological amelioration are the way to improve saline and alkaline soils.

Keywords: Soil components, Soil (Pedosphere), Amendment of saline and alkaline soils

Introduction:

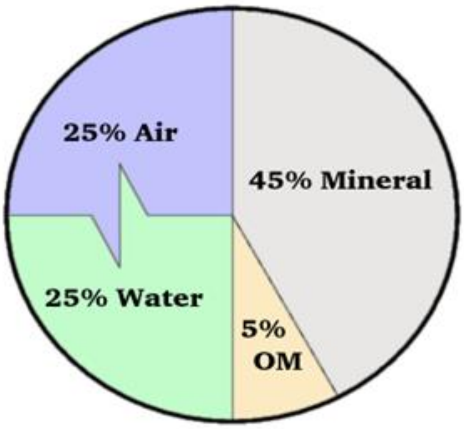


Fig. 1: Composition of an ideal soil (By vol.)

Fig. 2: Soil - natural medium for the growth of plants

Back to cultural roots

Christianity: The word **"Adam"** (man) is derived from Hebrew word **"Adama"** meaning "**earth"** or "**soil"**.

Vedas: The Vedas personify mother earth as the goddess **"Bhumi "**or **"Prithvi".**

Soil as a medium of a plant growth

Soil the interface of air, minerals, water and life. Soil occupies a central position in man's environment, the whole of which comprises lithosphere, hydrosphere, atmosphere and biosphere.

Green revolution

Green revolution states are now facing problems which are acting on the resource base that sustains crop production, water and soil are fast degrading while yield levels are static. Increasing population is proving harmful for us. Increasing population requires additional land, land is limited, it cannot be increased or decreased.

Saline and alkaline soils

Saline and alkaline soils and those that have an alkaline reaction or whose pH is greater than 7.0. This is due to the presence of an excess of sodium salts. Saline and alkali soils occur most commonly under arid climate (Source: Sahai,2011). When the anion Cl^{-1}, SO_4^{-2}, CO_3^{-2}, HCO_3^- Salt of (Cation) Na^+, Ca^{+2}, Mg^{+2}, K^+ are increased in soil, the soil becomes saline and alkaline. The saline and alkali soils are known under various names: "Reh" or "usar" (U.P.), "Chopan" in Mumbai, saline soils "Thur" and alkaline soil **"**Rakkar" or "Bara and Bari" in Punjab. The word "Usar" is derived from a Sanskrit word "ustra" Meaning sterile or Barren. Area under saline and alkaline soils are 7.0 M. ha (J. S. P. Yadav,1976). 187 M. ha has been affected by various soil degradation problems (Total area 329 M. ha).187 M. ha degradation land problem (57%of the total area), saline and alkali soils problem are one of them. In India per capita arable land availability has declined from 0.29 ha in 1965-66 to 0.15 ha in 2009-10 (Fertilizers Statistics 2011-12) and will shrink to less than 0.08 ha in 2025. Who had made observation" poor soils make poor people and poor people make the soil worse" (Source: Bennett,1939).

Saline and Alkali soils (Formation)

1. Arid and semi-arid climate: They are formed in arid and semi-arid regions, which have very low rainfall and high evaporation.

2. **Poor drainage of soil:** During the period of high rainfall, the salts leach from the upper layer and, if the drainage is impeded, they accumulate in the lower layer. When water evaporates, the salt is left in the soil. Such soils are generally developed in low lying areas.

3. Overflow of sea water over land: Low lying areas near the sea which get sea water during tides. Salt water accumulates and enriches the soil with salt.

4. Salts blown by wind: In arid regions near the sea, lot of salt is blown by wind year after year and gets deposited on the land. Due to low rainfall, they are not washed back to sea and thus add salinity to the land. The salinity of Rajasthan has mostly developed, due to this reason.

5. Use of basic fertilizers: Use of basic fertilizers like $NaNO_3$ and KNO_3 etc. may develop alkalinity in soil.

6. Parent rock materials: Soil develops from saline nature of parent rock materials, soil would be saline e.g., Gabbro, Basalt etc. (Source: Agrawal and Gupta, 1968).

Area where saline and sodic soils (Salt-affected soils) occur

Saline and sodic soils are found in the following areas in India:

1. Alluvial plain areas of Ganga: U.P., Delhi, Haryana, Punjab, Bihar and some areas of Rajasthan (3.50 M. ha).

2. Area of regur soil: Maharashtra, M.P., Rajasthan and Gujarat (1.42 M. ha)

3. Dry coastal area: Dry area of Gujarat near sea (0.71 M. ha).

4. Moist coastal area: West Bengal, Orissa, Andra pradesh, Maharashtra, Tamil nadu and Kerala (1.39 M. ha). Sodic soils of the Indo-Gangetic plains alone account for roughly $1/3^{th}$ of the 7.0 M. ha of the salt affected soils in India (Haryana, Punjab, U.P., Bihar, Rajasthan and M.P 2.5 M. ha).

Total Approx. Area:7.02 M. ha (Saline and Sodic or Alkali Soils in India).

(Source: Bhumbla, 1977)

How can the saline and sodic soils be identified?

Saline soils

i. A white or brownish white layer of salt ($NaCl$ and Na_2SO_4) is seen on the saline soils during summer. This layer disappears on irrigation or rainfall (Source: Singh,2018)

Sodic soils

i. Upper surface of sodic soils looks black due to dissolution of organic matter in water.

ii. The plants are charred in black alkali (sodic soils) soils.

iii. Sodic soils are difficult to manage, often hard -setting, poor aeration and erosion.

(Source: Rathinasamy and Saliha 2014).

Nature and classification

Sl. No.	Characteristic	Saline Soil	(Alkali) non-saline alkali soil	Saline-alkali soil	Degraded alkali soil
1.	Content (Soil)	Excess of sodium soluble salts.	absence of soluble salt.	It is a stage of transition. Soil contains Na+ clay as well as soluble salts.	H+ ion in upper layer Na+ (Lower layer).

2.	Exchanged Ca/Na	Ca.	Na.	-	-
3.	Colour of soil	White.	Black.	-	Black lower layer.
4.	Presence of salt in the soil	Nacl, Na_2So_4.	Na_2 Co_3.	-	Na_2Co_3 (Lower level).
5.	ESP	< 15%	> 15%	> 15%	> 15%
6.	pH	7.5 to 8.5	8.5 to 10.0	8.5	More than 8.5
7.	EC	> 4 ds/m.	<4 ds/m.	> 4 ds/m.	< 4 ds/m.
8.	Total soluble salt content	>0.1%	<0.1%	> 0.1%	< 0.1%
9.	SAR	<13	>13	>13	
10.	Other Name	White alkali, (Hilgard) Brown alkali.	Black alkali, (Hilgard) alkali soil, sodic soil.	Usar soil.	Solod, soloth,

Solonchaks: Saline soils (Russian local name)

Solonetz: Alkali soils (Russian local name)

(Source: Schroeder, 1984).

Facts

Soil structure: In alkali condition, soil is dispersed and becomes compact. The prism-like structures are commonly formed in sodic soils.

Soil texture: Coarse to moderately coarse soil texture (Sandy texture or loamy sand texture or sandy loam soil texture).

Soil horizon: B

Bulk density: Bulk density of coarse textured soils varies from 1.40 to 1.72Mg/m^3 (Sandy loam: 1.50 Mg/m^3, Loamy sand: 1.67 Mg/m^3, Loam: 1.39 Mg/m^3).

Particle density: The particle density of saline and alkali ranges from 2.60 Mg/m^3 to 2.75 Mg/m^3 (Source: Singh, 2018).

Climate: Saline and alkali soils occur most commonly under arid and semi- arid regions which have very low rainfall and high evaporation...

Area in India: Salinity (4.5 M. ha) and Alkalinity (2.5 M. ha)

Clay minerals: Illite and Chlorites are dominant

Anion not present in saline soils:CO_3

Absorption: Hindrance in water absorption.

Rainfall: Low

P-fixation in alkaline soils: pH 6.0-10.0 (Source: Biswas and Mukherjee, 2011).

Zn-fixation: Generally, Zn-fixation is found at high pH value (Sodic soils)

More toxic to roots: $NaCO_3$ (Source: Mehra, 2013).

Availability: Alkali or sodic soils decreases the availability of many plant nutrients like P, B, Ca, Mg, N, S, Fe, Cu, Mn and Zn. Mo availability is higher under sodic soils. (Source: Chavan and Patil,2018)

Deficiencies: The presence of excess Na in Sodic soil may induce deficiencies of cations Ca and Mg. Saline soils may be deficiency of Fe, Cu and Zn.

Organic matter: Alkali /sodic soils are generally poor in organic matter.

Toxicity: The more adsorption of B and Mo in sodic soils, makes toxic to plants.

Slick Spots: When alkali (Sodic soils) occur in small, irregular areas in arid and semi-arid regions, they are called "Slick Spots" (Source: Jha,1973).

Reclamation of saline and alkali soils

Physical or mechanical amelioration

1. Scraping: scraping of salt affected patches (15-30 cm depth) scraping helps to remove salt. This is not good method, and salinity again develops on such land (Bottom to Top).

2. Leaching: amount of water wasted except evaporation and transpiration from the soil.

3. Trenching: trench is made, and this trench or ditch is refilled up with soils of next trench. This method is temporary, salts come again capillary action on the upper surface. This method is very dear and labourful.

4. Washing out soluble salt: Watering the field, salt dissolve in upper surface, to remove the salt from the field. This method is good for such areas where the water is cheap and Adequate Quanties.

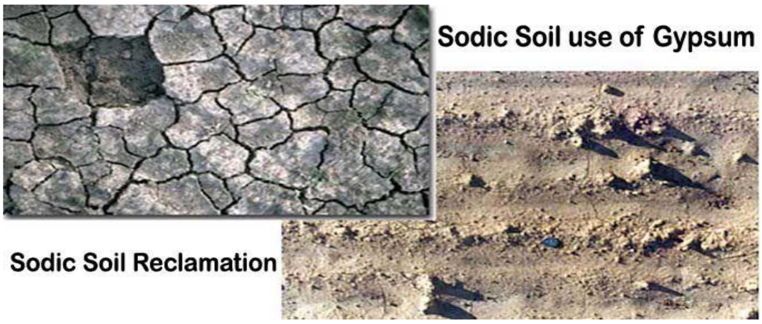
5. Drainage: Removal of excess water by artificial methods from the Agricultural land for production of crops.

6. Profile inversion: by using bulldozer.

7. Ploughing and leveling: Ploughing and leveling of the land (Source: Bhumbla, 1973).

Chemical amelioration

i) **Gypsum ($CaSO_4.H_2O$):** Gypsum uses the largest for reclaiming alkali soil. Gypsum replaces Na from soil and changes it into Ca soil.



(Source: https://www.constructioncost.co/sodic-soils.html)

ii) Pyrites (FeS_2): On using pyrites in usar soil extra benefit is that plant get Fe and S Nutrients from FeS_2. (Source: Mehta, 1983).

iii) Sulphur: when Sulphur is spread on the Soil, it is oxidized to sulphuric acid, which converts $NaCO_3$ into Na_2SO_4.

$$2S + 3O_2 \longrightarrow 2SO_3$$

$$SO_3 + H_2O \longrightarrow H_2SO_4$$

$$Na_2CO_3 + H_2SO_4 \longrightarrow CO_2 + H_2O + Na_2SO_4 \text{ (leaching)}$$

iv) Limestone: Na present on soil replaced by Ca

$$2Na + CaCO_3 \longrightarrow Ca + Na_2CO_3.$$

Soil amendment

Chemical amendment	Suitable for
Gypsum	Saline and alkaline soils have pH upto 9.0
Sulphur	Alkaline and saline-alkali soils with pH upto 9.0
Iron sulphate	Alkaline and saline-alkali soils with pH ranging up 9.0
Limestone	Saline soil with pH less than 8.0
Pyrites	Sodic (alkali) soil.

(Source: Yawalkar et al.,2002)

List of recommended fertilizer on problem soils

Nature of problem soil	Nutrient	Name of fertilizer recommended to supply the nutrient
1.Saline	N and P	$(NH_4)_2$ SO_4, CAN, SSP, Triple Super Phosphate
2.Alkali	N and P	$(NH_4)_2$ SO_4, NH_4NO_3, DAP
3.Saline-alkali	N and P	$(NH_4)_2SO_4$, DAP, Triple Super Phosphate

(Source: Das, 1993)

Biological amelioration

1. Application of organic manure: FYM compost, poultry manure etc.

2. Application of Bio-fertilizer: VAM, PSB, Azobactor etc.

3. Crop rotation:

a) Paddy + Berseem b) Dhaincha + oat c) Dhaincha + Barley

4. Grow of Acacia: Acacia corrected saline and alkaline soils about 18-20 years, become acacia have found taproot, taproot penetrate hard surface thus improve drainage and soil become correct.

5. Green manure: Growing Green manure crops like Dhaincha, mung, Sunn hemp etc.

6. Growing of alkali tolerant crops and plants: Such as Sugarbeet, potato, rice, acacia, Sunn hemp etc. in such soils successfully reduce alkaline.

Salt and alkali resistant crops

Highly salts resistant crops	Moderately resistant crops	Low salt resistant crops
Barley, Sugar beet, Cotton etc.	Wheat, Rice, Maize, Cabbage, Cauliflower, Carrots, Onions, Peas etc.	Bean, radish etc.

Suitable for planting in saline and alkaline soils (Fruits)

Ber, Aonla, Phalsa, Jamun, Guava etc.

Salt tolerant crops (Highly)

Barley, cotton, Sugarbeet, tobacco, turnip, Dhaincha etc.

Conclusion:

The most important natural resources from the point of agriculture are soil. The soil, however, provides proper anchorage for the plants and serves as reservoir for water and nutrient reservoir for the plants. Today we have a big problem, we have to save fertile land from becoming barren land. At the same time, more crops have to be produced from the land in modern ways and environment will have to be green with environment protection. Preventive measures such as reduction in using inorganic fertilizers and pesticides, using organic manure, salt tolerant crops, providing proper drainage. Protecting our natural resources(soil) from contamination and embracing eco-friendly life concern. Soil-Plant-Animal-Atmosphere Continuum managing properly for posterity and conserve for posterity.

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NATURAL FARMING: CULTIVATING SUSTAINABILITY

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Natural farming and organic farming are both sustainable, chemical-free agricultural systems, but they differ significantly in their approaches and philosophies. Natural farming emphasizes minimal intervention and reliance on natural processes, while organic farming allows for more controlled practices and external inputs.

Key Differences between Natural farming and Organic farming

Key Differences	**Natural farming**	**Organic farming**
Intervention	Natural farming advocates for zero external inputs, including both chemical and organic fertilizers, relying on natural processes like decomposition and nutrient cycling within the ecosystem.	Organic farming, while also avoiding synthetic chemicals, allows for the use of certain approved organic inputs like compost, vermicompost, and natural pesticides.
Soil Management	Natural farming discourages plowing, tilling, and weeding, encouraging natural decomposition on the soil surface.	Organic farming, while promoting these practices, may involve more intensive soil management techniques.
Inputs	Natural farming is based on on-farm inputs like cow dung and urine-based preparations, and biomass recycling through mulching.	Organic farming may utilize off-farm organic and biological inputs and mineral corrections.
Certification	Natural farming often lacks specific certification standards.	Organic farming is governed by established certification bodies.
Cost	Natural farming is generally a low-cost method, relying on on-farm resources.	Organic farming can be more expensive due to the need for inputs and labor.

In essence, natural farming is a philosophy of minimal intervention, working with nature's processes, while organic farming is a system with defined practices and standards, allowing for some external inputs within a sustainable framework.

Natural farming, also known as Prakritik Kheti, is a chemical-free, livestock-based farming system that emphasizes ecological processes and biodiversity. It integrates crops, trees, and livestock, relying on locally available resources and traditional farming practices. Natural farming aims to minimize external inputs, reduce costs, and improve soil health and environmental sustainability.

Concept of Natural Farming

Natural Farming is a chemical-free farming system rooted in Indian tradition enriched with modern understanding of ecology, resource recycling and on-farm resource optimization. It is considered as agro-ecology based diversified farming system which integrates crops, trees and livestock with functional biodiversity. It is largely based on on-farm biomass recycling with major stress on biomass mulching, use of on-farm cow dung-urine formulations; maintaining soil aeration and exclusion of all synthetic chemical inputs. Natural farming is expected to reduce dependency on purchased inputs. It is considered as a cost- effective farming practice with scope for increasing employment and rural development.

Scenario

Natural farming is a method of agriculture that works with nature, minimizing human intervention and synthetic inputs. It emphasizes using locally available resources, on-farm biomass recycling, and indigenous practices to create a sustainable and resilient farming system. The goal is to enhance soil health, biodiversity, and ecosystem services while producing healthy food and reducing reliance on external inputs.

Origin of Natural Farming

Natural farming, also known as the Fukuoka Method, is an ecological farming approach developed by Masanobu Fukuoka, a Japanese farmer and philosopher. It emphasizes working with nature, minimizing human intervention, and avoiding synthetic inputs. The concept gained recognition with the publication of Fukuoka's book, The One-Straw Revolution, in 1975. The Fukuoka Method, also known as Natural Farming or Do-Nothing Farming, is a system developed by Masanobu Fukuoka, emphasizing minimal human intervention in agriculture. It focuses on observing and working with the natural processes of an ecosystem to grow food, rather than imposing external inputs or disrupting the soil. Key practices include using local seeds, cover crops, and seed balls to minimize soil preparation.

Core Principles of the Fukuoka Method of Natural Farming:

- **Minimal Intervention:**

Fukuoka's approach minimizes human interference with natural cycles. This includes avoiding plowing, weeding, and the use of chemical fertilizers and pesticides.

- **Observational Learning:**

Farmers are encouraged to observe natural ecosystems and learn from them, understanding how plants and animals interact to create a balanced environment.

- **Working with Nature:**

Instead of fighting against natural processes, the Fukuoka Method seeks to work with them. This includes using natural methods like cover cropping and mulching to improve soil health and reduce the need for external inputs.

- **Local Seeds and Varieties:**

Fukuoka emphasized the use of local, naturally adapted seeds and crop varieties, believing they are more resilient and productive in their local environment.

- **Seed Balls:**

Seed balls, also known as earth dumpings or nendo dango, are a unique technique used in natural farming, particularly associated with Masanobu Fukuoka, that involves encasing seeds in a protective ball of clay, compost, and other materials. This method allows for easy dispersal of seeds, protects them from predators and harsh weather conditions, and promotes germination in suitable environments.

Key practices in Fukuoka Method:

- **Direct Seeding:**

Instead of transplanting seedlings, seeds are sown directly into the soil, often using seed balls.

- **Cover Cropping and Mulching:**

Cover crops are planted to suppress weeds, improve soil fertility, and provide biomass for mulching.

- **No-Till Farming:**

    The soil is not tilled, minimizing disruption to the natural soil structure and microbial life.

- **Crop Rotation:**

    Different crops are grown in rotation to maintain soil fertility and reduce pest and disease outbreaks.

- **Natural Pest and Disease Management:**

    The Fukuoka Method prioritizes working with nature, not against it, to manage pests and diseases. This approach relies on building healthy ecosystems i.e. reliance on natural predators and the overall health of the ecosystem to control pests and diseases and fostering natural pest control mechanisms rather than using external inputs like pesticides or fertilizers.

In essence, the Fukuoka Method is not about eliminating pests and diseases entirely, but rather about understanding and working with natural processes to create a balanced ecosystem where plants can thrive despite the presence of pests and diseases.

Importance of Natural Farming

Natural farming is gaining importance due to its numerous benefits for the environment, human health, and economic sustainability. It promotes ecological balance, enhances soil health, reduces reliance on synthetic inputs, and offers a path towards more resilient and profitable agriculture.

1. Environmental Benefits:

- **Soil Health:**

    Natural farming practices like mulching and composting improve soil fertility and water retention by fostering beneficial microorganisms and increasing organic matter.

- **Water Conservation:**

    Reduced reliance on synthetic inputs and the use of techniques like mulching and drip irrigation minimize water usage.

- **Reduced Pollution:**

    Natural farming avoids synthetic chemicals, reducing soil, water, and air pollution from pesticides and fertilizers.

- **Climate Change Mitigation:**

    By promoting healthy soil that acts as a carbon sink, natural farming can help mitigate climate change.

2. Economic Benefits:

- **Reduced Costs:**

    Natural farming minimizes the need for expensive synthetic inputs, lowering production costs.

- **Increased Income:**

Natural farming can lead to higher yields and reduced expenses, potentially boosting farmers' incomes and promoting sustainable livelihoods.

- **Job Creation:**

The emphasis on local resources and ecological practices can create new employment opportunities in rural areas.

3. Health Benefits:

- **Nutrient-Rich Food:**

Food grown through natural farming is often richer in nutrients and free from harmful residues of synthetic chemicals.

- **Reduced Health Risks:**

Eliminating synthetic chemicals reduces health risks associated with pesticide and fertilizer exposure.

4. Social Benefits:

- **Sustainable Livelihoods:**

Natural farming promotes sustainable agriculture, offering a viable and profitable livelihood for farmers.

- **Food Security:**

By improving soil health and crop yields, natural farming can contribute to food security.

- **Rural Development:**

Natural farming can revitalize rural communities by creating jobs and promoting sustainable practices.

5. Addressing Key Challenges:

- **Food Security:**

Natural farming offers a solution to food insecurity by enhancing production through sustainable methods.

- **Farmer Distress:**

By reducing input costs and promoting resilient farming systems, natural farming can alleviate farmer distress.

- **Environmental Degradation:**

Natural farming addresses environmental challenges like soil degradation and water pollution, promoting ecological balance.

Natural farming in India

Natural farming in India has deep historical roots, evolving from ancient sustainable practices to modern approaches like Zero Budget Natural Farming (ZBNF). Traditional Indian agriculture, described in ancient texts like the Rig Veda, emphasized the harmony with nature and the preservation of ecosystems. The Green Revolution in the 1960s led to a shift towards chemical-intensive farming, but concerns about its long-term effects have spurred a resurgence of interest in natural farming methods.

Historical Context:

- **Ancient Civilizations:**

  Ancient Indian civilizations, particularly the Indus Valley Civilization and the Vedic period, practiced natural farming principles long before modern environmental movements. They employed sustainable methods like crop rotation, organic matter incorporation, and water management to maintain soil fertility and enhance crop yields. Sustainable practices like composting, crop rotation, and natural pest control were integral to Indian agriculture long before the introduction of synthetic inputs. The concept of "**Vaniki**," or forest farming, promoted the integration of agriculture with forestry.

- **Vedic Period:**

  During the Vedic period in India, agriculture was a foundational aspect of life, characterized by natural farming practices that were deeply intertwined with the environment and Vedic philosophy. This era saw the use of cattle dung for soil fertility, a profound understanding of natural cycles, and the integration of plants and animals into farming systems. Vedic farmers also utilized traditional knowledge, passed down through generations, to adapt to diverse ecological conditions and ensure sustainable food production. The Rig Veda and other ancient texts contain references to natural farming methods that highlight the importance of ecological balance.

- **Influence of Philosophies:**

  Natural farming in India is significantly influenced by various philosophical underpinnings, including traditional ecological knowledge, Gandhian philosophy, and the principles of Masanobu Fukuoka's natural farming. These philosophies emphasize working with nature, minimizing external inputs, and promoting ecological balance. Jainism and Buddhism, with their emphasis on non-violence and respect for all living beings, also influenced agricultural practices, promoting methods that minimized harm to the environment.

- **The Green Revolution:**

  The Green Revolution in India, while significantly boosting food production and achieving self-sufficiency, had a mixed impact on natural farming. While it led to increased yields and reduced reliance on imports, it also promoted intensive chemical agriculture, which can be detrimental to soil health and biodiversity. This shift away from traditional farming practices has created challenges for the revival of natural farming, but also highlighted the need for sustainable alternatives. In the mid-20th century, the Green Revolution focused on increasing food production through the use of high-yielding seeds, chemical fertilizers, and pesticides. This shift led to a decline in traditional farming practices.

Modern Revival:

- **Concerns about Chemical Farming:**

  In India, there's a growing movement towards natural farming as a sustainable alternative to chemical farming, driven by concerns about its environmental and health impacts. This revival is fueled by the Green Revolution's negative consequences, such as soil degradation and rising input costs, leading to farmer debt and distress. Natural farming, with its focus on ecological balance and minimal external inputs, is gaining traction as a viable solution. Growing awareness of the negative impacts of chemical agriculture, such as soil degradation and water pollution, has fueled the revival of natural farming.

- **Zero Budget Natural Farming (ZBNF):**

  Zero Budget Natural Farming (ZBNF) is a natural farming method in India that aims to eliminate the cost of agricultural inputs by utilizing locally available resources and natural processes. It emphasizes using cow dung, cow urine, jaggery, and other natural substances for seed treatment, soil enrichment, and pest management, rather than relying on external chemical fertilizers and pesticides. ZBNF is a grassroots movement that has gained traction as an alternative to the Green Revolution's reliance on chemical inputs. ZBNF developed by Subhash Palekar, ZBNF draws inspiration from traditional Indian practices and forest ecosystems, emphasizing the use of natural inputs like cow dung and urine to nourish the soil.

- **Andhra Pradesh Community Managed Natural Farming (APCNF):**

  Vide G.O.Ms No. 197 Finance (R&E) Department dated 04 October 2014 issued by State of Andhra Pradesh, Rythu Sadhikara Samstha has been established as a not-for-profit company under Section 8 of the Companies Act 2013 to create integrated institutional mechanism for all programmes, schemes and activities intended for farmer's empowerment, encompassing welfare, development, capacity enhancement, credit flow, financial support and allied empowerment activities. Rythu Sadhikara Samstha in English can be read as Farmer Empowerment Organisation. Andhra Pradesh Community Managed Natural Farming (APCNF) is being implemented by Rythu Sadhikara Samstha as per GO RT No. 764, dated 10-11-2016. This program, promotes natural farming practices through farmer-to-farmer knowledge dissemination and community participation.

- **Pre-Monsoon Dry Sowing (PMDS):**

  Pre-Monsoon Dry Sowing (PMDS) in Natural Farming in India involves planting seeds before the monsoon rains arrive, utilizing the moisture from dewfall and soil retention to support germination and early growth. This practice, often combined with mulching and natural inputs, allows for a longer growing season and increased crop diversity, even in rain-fed areas. In drought-prone regions, PMDS is used to harness dew moisture, enhance soil humus, and improve water retention.

Concept of PMDS:

- PMDS aims to keep the soil covered with living plants for as much of the year as possible, a core principle of natural farming.
- It involves sowing seeds before the monsoon, even when the soil is dry, and relying on the subsequent rains to initiate germination and growth.
- This contrasts with traditional farming practices where planting is often delayed until the monsoon rains have arrived and saturated the soil.

Methods:

- **Direct Sowing:** Seeds are sown directly into dry soil, often with the help of techniques like seed pelletization to protect them from the harsh conditions.
- **Intercropping:** If PMDS wasn't done before the main crop, intercropping can be used by planting seeds between existing standing crops.
- **Seed pelletization:** This technique involves coating seeds with a protective layer to enhance their survival in dry conditions until the monsoon arrives.
- **Soil Amendments:** The use of natural farming techniques like mulching, composting, and inoculams can improve soil health and germination rates.
- **Benefits of PMDS:**
- **Year-round green cover:** Keeps the soil covered with live plants, which is beneficial for soil health and biodiversity.
- **Improved soil health:** Living roots help improve soil structure, fertility, and water retention.
- **Potential for increased yields:** By ensuring timely germination and growth, PMDS can lead to better crop establishment and potentially higher yields.
- **Drought resilience:** Crops sown before the monsoon may be better able to withstand dry spells.
- **Reduced input costs:** Natural farming methods like PMDS can reduce the need for chemical fertilizers and pesticides.

Key aspects of PMDS in natural farming:

- **Seed Coating:** Beejamrit, a microbial seed coating, is applied to protect seeds and enhance germination. It typically includes cow dung, cow urine, and a handful of soil from the field.
- **Soil Amendments: Jeevamrit**, a microbial soil drench, and mulching are used to improve soil fertility and moisture retention. It includes cow dung, cow urine, jaggery, pulse flour, and a handful of soil from the field. Beejamrit is primarily a seed treatment, while Jeevamrit is a soil application, both aiming to enhance soil fertility and plant growth.
- **Diverse Crops:** PMDS often involves planting a mix of 8-15 different crops, promoting biodiversity and resilience.
- **Mulching:** Mulching with organic materials like dried biomass helps conserve moisture, suppress weeds, and improve soil structure.
- **Green Manure:** The mixed crops grown during PMDS are often plowed back into the soil as green manure, enriching it with nutrients.
- **Water Conservation:** Mulching and the use of diverse crops help to harness atmospheric moisture and reduce water evaporation.
- **Climate Resilience:** PMDS enhances soil health and moisture retention, making crops more resilient to drought and extreme weather events.

In essence, PMDS is a natural farming practice that leverages the power of microbial activity, organic matter, and diverse cropping systems to create a thriving and resilient ecosystem within the agricultural field.

- **Emphasis on Indigenous Seeds and Practices:**

  Natural farming in India strongly emphasizes the use of indigenous seeds and traditional practices. This approach is rooted in the belief that local varieties are better adapted to the specific agro-climatic conditions of a region and promote biodiversity, resilience, and sustainability. Indigenous knowledge systems, developed over generations, offer valuable insights into soil health, water management, and pest control, which are incorporated into natural farming methods. Modern natural farming initiatives often prioritize the use of indigenous seeds and traditional knowledge.

- **Current Status of Natural Farming in India**

  Natural farming in India is gaining momentum, with several states actively promoting it through various initiatives and schemes. While it's still a relatively nascent practice compared to conventional farming, it's gaining traction as a sustainable and eco-friendly alternative. Many states are already fallowing natural farming and have developed successful models. State of Andhra Pradesh, Karnataka, Himachal Pradesh, Gujarat, Uttar Pradesh and Kerala are among the leading states. Currently, the acceptance and adoption of natural farming systems are at early stages and gradually gaining acceptance among the farming community.

Key aspects of natural farming's current status in India:

- **State-level initiatives:**

Several Indian states are actively promoting natural farming through dedicated programs, subsidies, and awareness campaigns. Andhra Pradesh is a frontrunner, implementing large-scale natural farming through programs like Community-Managed Sustainable Agriculture (CMSA). Other leading states include Gujarat, Himachal Pradesh, Odisha, Madhya Pradesh, Rajasthan, Uttar Pradesh, and Tamil Nadu. These states have adopted state-led programs and schemes to encourage natural farming practices, with a focus on reducing input costs, enhancing soil health, and promoting climate resilience.

- **Prominent states and Area coverage:**

Many states have taken up initiatives for natural farming promotion Andhra Pradesh, Gujarat, Himachal Pradesh, Odisha, Madhya Pradesh, Rajasthan, Uttar Pradesh and Tamil Nadu are among the leading states. As of now, more than 10 lakh ha. area is covered under natural farming in India (National Mission on Natural Farming, GOI).

- **Financial support:**

The National Mission on Natural Farming (NMNF) is a centrally sponsored scheme launched by the Indian government to promote chemical-free, sustainable agricultural practices. It aims to shift towards ecologically healthy farming methods, improve soil health, and reduces reliance on external inputs, thereby increasing farmer income and promoting climate resilience.

- **Growing awareness:**

Natural farming in India is gaining traction, with increasing awareness and adoption among farmers, particularly in states like Andhra Pradesh, Gujarat, and Himachal Pradesh. While still in its early stages, it's estimated that over 1 million hectares are now under natural farming practices. The movement is driven by growing consumer demand for organic and chemical-free food, and the potential for improved soil health, environmental sustainability, and farmer livelihoods. There's increasing awareness among farmers and consumers about the benefits of natural farming, including its environmental and health advantages.

- **Challenges:**

Natural farming in India faces several challenges despite its potential benefits. Key issues include a lack of awareness and training among farmers, resistance to change from those accustomed to conventional methods, limited budgetary support and policy focus on chemical farming, and concerns about lower yields and market access for natural produce. Natural farming still faces challenges like the need for more scientific validation, long-term studies, and addressing concerns about yield stability and market access.

- **Zero Budget Natural Farming (ZBNF):**

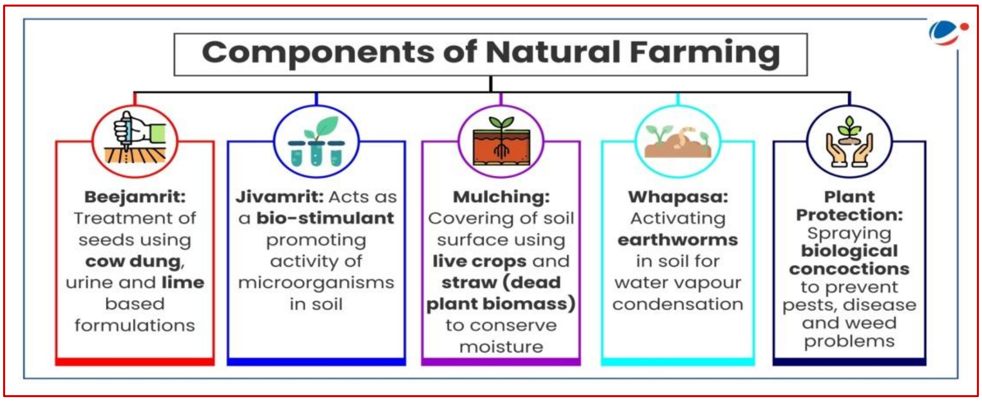
Zero Budget Natural Farming (ZBNF) is a farming method that aims to eliminate or significantly reduce the cost of agricultural production by avoiding the use of synthetic fertilizers and pesticides. It emphasizes using locally available natural inputs and promoting ecological balance within the farming system. The core idea is to achieve "zero cost" for crop production by relying on natural processes and resources. This specific model of natural farming, emphasizing minimal external inputs, is also gaining popularity and is being evaluated for its effectiveness in different agricultural systems.

- **Government support:**

The Union Budget often includes provisions for natural farming, highlighting its importance in the government's agricultural policy. The Indian government is actively supporting natural farming through various schemes and missions with a focus on reducing chemical usage and promoting sustainable practices. The National Mission on Natural Farming (NMNF) is a key initiative with a financial outlay of ₹2481 crore, aiming to cover one crore farmers. This mission focuses on transitioning farmers to chemical-free methods rooted in traditional knowledge and local ecosystems.

Components of Natural Farming

Natural farming, a sustainable agricultural approach, focuses on rejuvenating soil health, improving yields, and conserving the environment without relying on synthetic inputs. It emphasizes minimal soil disturbance, organic and natural practices, and water conservation. Key components include promoting biodiversity, recycling biomass, using cow dung and urine-based formulations, and employing botanical concoctions for pest control.



1. Soil Health and Fertility: Natural farming promotes soil health and fertility by focusing on biological processes rather than external inputs. Key components include using on-farm inputs like Jeevamrit and Ghanajeevamrit, promoting mulching, employing intercropping, and ensuring a healthy soil food web. These practices enhance microbial activity, improve soil structure, and increase nutrient availability for plants.

- **Minimal Soil Disturbance:**

Minimal soil disturbance in natural farming, also known as conservation agriculture, involves reducing or eliminating tillage practices to maintain soil health and structure. This approach focuses on practices like no-till farming and direct seeding, where the disturbed area is limited to a narrow strip or a small percentage of the field. The goal is to minimize disruption to the soil's natural processes, enhancing its fertility and overall ecosystem function.

- **Organic Matter:**

In natural farming, organic matter refers to the decomposed remains of plants and animals found in the soil, including living organisms, fresh residues, and well-decomposed material. It's a crucial component of fertile soil, acting as a food source for beneficial microbes and improving soil structure.

- **Cow Dung and Urine-Based Inputs:**

Cow dung and urine are valuable inputs in natural farming, serving as natural fertilizers and potentially as biopesticides. Cow dung improves soil structure, aeration, and water retention, while cow urine, rich in nitrogen and other nutrients, can be used as a foliar spray or applied to the soil. Utilizes Jivamrit (a fermented microbial culture) and Ghanajivamrit (a solid form of Jivamrit) derived from cow dung, urine, jaggery, and other natural ingredients to enhance soil fertility and microbial activity.

- **Seed Treatment:**

Seed treatment in natural farming involves using biological and physical methods to enhance seed performance and protect them from diseases and pests, ultimately promoting healthy plant growth. This approach focuses on improving germination rates, seedling vigor, and crop health while minimizing the use of synthetic chemicals. Employing of Beejamrit, a seed treatment made from cow dung, urine, and other natural ingredients, to protect seeds from diseases and pests.

- **Mulching:**

Mulching in natural farming involves covering the soil surface with organic materials like straw, leaves, or crop residues. This practice offers several benefits, including moisture conservation, weed suppression, and improved soil health by enhancing microbial activity and nutrient cycling. Mulching also helps to regulate soil temperature, prevent erosion, and reduce the need for synthetic inputs. Using a layer of organic material (like straw or leaves) on the soil surface to conserve moisture, suppress weeds, and improve soil health.

2. Biodiversity and Integrated Systems: Natural farming, when integrated with Integrated Farming Systems (IFS), emphasizes biodiversity and efficient resource utilization through various interconnected components. These components, including crops, livestock, trees, and aquaculture, work synergistically to create a closed-loop system that minimizes waste and maximizes resource utilization.

- **Mixed cropping:**

Mixed cropping, also known as polyculture, involves growing two or more crops simultaneously on the same land. In natural farming, this practice is employed to mimic natural ecosystems, enhance soil health, and reduce reliance on external inputs like chemical fertilizers and pesticides. Incorporation of a variety of crops in the same field will be practiced to enhance biodiversity and reduce pest and disease outbreaks.

- **Integration of Trees and Livestock:**

Integrates trees into the farming system and utilizes livestock (especially desi cows) for manure and other inputs, promoting a holistic and sustainable ecosystem.

3. Pest and Disease Management: Natural farming pest and disease management relies on creating a healthy ecosystem rather than solely relying on external interventions. Key components include fostering a healthy soil, promoting crop resilience, utilizing biological control methods, and employing natural pest repellents and botanical extracts. This holistic approach aims to enhance the natural defenses of the crops and the surrounding environment to minimize pest and disease outbreaks. Effective pest and disease management is a cornerstone of natural farming. This approach harnesses natural predators, plant diversity, soil health, and traditional practices to tackle pests and diseases with minimal environmental impact.

- **Cultural Practices:**

Cultural practices play a pivotal role in natural farming for managing pests and diseases. Crop rotation, for instance, involves changing crops seasonally, which disrupts the life cycles of pests and diseases and helps prevent their build-up in the soil. Intercropping, where two or more crops are grown together, also reduces the incidence of pests; a classic example is planting marigold as a border crop to repel nematodes, while legumes enrich the soil with nitrogen and attract beneficial predators. Sanitation is equally crucial, as removing diseased plant debris and infested material from the fields eliminates sources of infection, and regular field inspections enable early identification and timely removal of affected plants. Proper plant spacing is another effective measure, since it ensures good air circulation within the crop canopy and thereby reduces the humidity levels that favor fungal diseases.

- **Physical and Mechanical practices:**

Physical and mechanical control strategies are employed to further manage pest populations. Manual removal entails handpicking visible pests such as caterpillars and beetles, as well as their egg masses, while destroying infected plant parts to prevent the spread of disease to healthy plants. The use of traps and barriers is another essential tactic; for example, sticky traps are set up to capture flying insects, while physical barriers such as nets and row covers are installed to protect crops during their most vulnerable growth stages, reducing the risk of infestation and disease transmission.

- **Botanical extracts:**

Botanical extracts, derived from various plant parts, are increasingly utilized in natural farming as biostimulants and bio-pesticides. They offer a sustainable alternative to synthetic chemicals, promoting plant growth, enhancing resistance to stress, and protecting crops from pests and diseases. Employing of plant-based pest control methods like Neemastra, Brahmastra, Tobacco decoction, chilli garlic extract and Dashaparni (preparations using cow urine, cow dung, and various plant extracts) to manage pests and diseases.

- **Natural Predators:**

Natural predators are an essential component of ecological pest management in natural farming systems. These beneficial organisms feed on or parasitize pest species, thereby keeping their populations in check without the need for chemical interventions. For example, ladybird beetles (ladybugs) are voracious consumers of aphids, which are common sap-sucking pests affecting a variety of crops. Similarly, lacewing larvae prey on soft-bodied insects such as whiteflies and caterpillars. Other important natural predators include spiders, which trap and consume many types of pest insects, and predatory wasps, which lay their eggs inside caterpillars or aphids, ultimately destroying these pests from within. Birds, frogs, and bats also contribute to pest control by feeding on insects and their larvae. By encouraging the presence of natural predators through practices such as maintaining flowering plants and creating natural habitats around farmlands, farmers can foster a balanced ecosystem where pest outbreaks are naturally regulated.

- **Parasitoids and microbial pesticides:**

The use of parasitoids and microbial pesticides forms an important part of pest and disease management in natural farming. Parasitoids are specialized insects, such as certain species of wasps that lay their eggs inside or on pest insects like caterpillars or aphids; when the eggs hatch, the developing larvae feed on the host, ultimately killing it. For example, the *Trichogramma* species is widely used to control egg-laying pests like borers in crops, and *Encarsia fumasorosea* is a valuable parasitoid for managing whitefly populations in vegetable and ornamental crops. Microbial pesticides, meanwhile, utilize beneficial microorganisms to target pests and diseases. *Bacillus thuringiensis* (Bt) is a well-known example—a soil-dwelling bacterium that produces toxins harmful to caterpillars when ingested, providing effective control without harming beneficial insects or the environment. Similarly, *Trichoderma* species are fungi deployed to suppress soil-borne plant diseases by outcompeting or parasitizing pathogenic fungi. By relying on parasitoids and microbial pesticides, natural farming enhances crop protection in a sustainable, eco-friendly way that minimizes the negative impacts associated with synthetic chemical use.

4. Water Conservation: Water conservation in natural farming is achieved by employing practices that minimize water use, enhance soil moisture retention, and reduce reliance on external water sources. Key strategies include using mulch and compost, adopting efficient irrigation techniques like drip irrigation, and implementing rainwater harvesting. These methods collectively promote sustainable water management in agricultural systems.

- **Water Harvesting:**

Water harvesting in natural farming involves collecting and storing rainwater for later use in agricultural practices. This technique is particularly valuable in arid and semi-arid regions where water scarcity is a challenge. By collecting runoff from various surfaces like roofs, courtyards, or even specialized catchments, farmers can create a sustainable water source for irrigation and other needs, reducing reliance on external water sources. It emphasizes the techniques to capture and conserve rainwater for irrigation.

- **Mulching:**

Mulching in natural farming involves covering the soil surface with organic materials like straw, leaves, or crop residues. This practice offers several benefits including moisture conservation, weed suppression, and improved soil health by enhancing microbial activity and nutrient cycling. Mulching also helps to regulate soil temperature, prevent erosion, and reduce the need for synthetic inputs. Mulching helps to retain soil moisture and reduces the need for frequent irrigation.

5. Reduced External Inputs:

- **No Synthetic Fertilizers or Pesticides:**

Natural farming, fundamentally eliminates the use of synthetic fertilizers and pesticides. It relies on natural processes and locally available resources to build healthy soil and manage pests. Key components include crop rotation, intercropping, mulching, and the use of natural pest control methods like botanical extracts. Therefore, avoids the use of synthetic chemical fertilizers, pesticides, and herbicides, promoting a chemical-free approach to agriculture.

- **Local Resources:**

Natural farming leverages local resources to create a self-sustaining and eco-friendly agricultural system. Key components include using local seeds, desi cow-based inputs, and on-farm generated biomass for soil enrichment and pest management. It also emphasizes biodiversity through mixed cropping and integrating trees and livestock. Hence, it relies on locally available resources and on-farm inputs, reducing the need for external inputs and promoting self-sufficiency.

Limitations of natural farming

Natural farming, while beneficial for the environment, faces certain disadvantages, primarily lower yields compared to conventional methods and higher production costs. It also requires more intensive labor, and the transition period can be challenging for farmers. Additionally, market limitations, like limited availability and higher prices, can affect both farmers and consumers.

Lower Yields:

- Organic farming, including natural farming, typically yields less than conventional methods due to the absence of synthetic inputs like fertilizers and pesticides.
- This yield gap can be significant, with some studies showing organic yields 19-25% lower than conventional yields.
- Inconsistent output is also a concern, as natural processes can be less predictable than synthetic interventions.

Higher Production Costs:

- Organic farming often requires more manual labor for tasks like weeding, pest control, and crop rotation.
- Certification costs for organic or natural farming can be high and time-consuming, adding to the financial burden on farmers.

Market Limitations:

- Organic products, including those from natural farming, may face limited market access, especially for small-scale farmers.

- The higher prices of organic and natural products can also restrict consumer demand, particularly in price-sensitive markets.

Transition Period Challenges:

- Farmers transitioning to natural farming may experience lower yields and economic uncertainties during the initial years as they adjust their practices.
- This transition period can be a barrier to adoption, requiring farmers to bear the costs of organic agriculture without immediate benefits.

Other Disadvantages:

- **Vulnerability to pests and diseases:**

Without the use of synthetic pesticides, organic crops can be more susceptible to pests and diseases, potentially leading to crop losses.

- **Skilled labor requirements:**

Natural farming can require specialized knowledge and skills for effective implementation.

- **Limited availability of produce:**

Organic and natural products may be less available in some markets, affecting consumer access.

Natural farming, in its entirety, encompasses a holistic, ecological approach to agriculture that minimizes or eliminates the use of synthetic inputs like chemical fertilizers and pesticides. It aims to work with nature, not against it, by mimicking natural ecosystems and promoting biodiversity.

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MICROBIAL BIOFERTILIZERS: SUSTAINABLE TOOLS FOR ENHANCING CROP PRODUCTIVITY AND SOIL VITALITY

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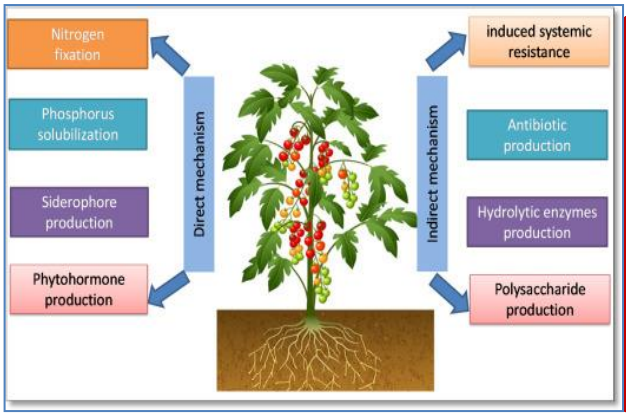
Introduction:

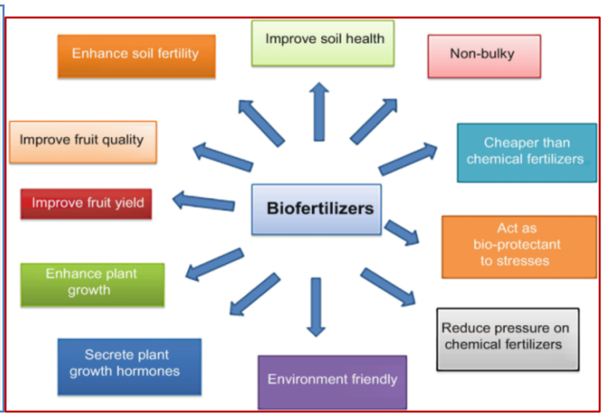
Biofertilizers are substances containing live microorganisms that enhance plant growth by improving nutrient availability in the soil. They are a sustainable and eco-friendly alternative to chemical fertilizers, promoting plant health and soil fertility. These microbial inoculants help plants access essential nutrients like nitrogen, phosphorus, and potassium, leading to increased crop yields. The term "biofertilizer" is a product which is not chemically synthesized, biodegradable, and can be used as a fertilizer. However, biofertilizer entail as a fertilizer containing living organisms which is classified as phosphate-solubilizing and nitrogen-fixing biofertilizers which contains fungi or bacteria. They have been employed in many kinds of formulations.

From the scientific point of view biofertilizer is an individual microorganism exerting plant growth promotion properties, but in the agronomical context this term pertains to product composed of beneficial strain(s), which are useful regarding nutrient mobilization, included in a carrier, possessing features that allow its storage at the time specified by the producer, and ready to effective application to the soil or plant. Term "biofertilizer" should not be used interchangeably not only with terms such as plant or animal manure, intercrop or fertilizers referring to combination of mineral and organic compounds, but also with bio-stimulants derived from microorganisms.

Biofertilizers are natural substances containing beneficial microorganisms that, when applied to seeds, plants, or soil, enhance plant growth by increasing the availability of essential nutrients. They are an environmentally friendly and cost-effective alternative to chemical fertilizers, promoting plant health and soil fertility through natural processes.

Biofertilizers are essentially formulations of living microorganisms, such as bacteria, fungi, and algae, that, when introduced to the soil, help plants access nutrients more efficiently. These microorganisms can fix atmospheric nitrogen, solubilize phosphorus, and produce growth-promoting substances that benefit plant growth.





Biofertilizers -Policies

Biofertilizers policy and programmes concerns related to use of chemical fertilizers have led to a desperate search for alternative non-chemical options. These include biofertilizers and organic fertilizers. These non-chemical options are considered critical to the transition from chemical-based to sustainable farming practices like organic and natural farming. Availability of cost-effective quality biofertilizers is, therefore, of utmost importance. Biofertilizers are ready to use live formulates of beneficial microorganisms that on application to seed, root or soil mobilizes nutrients through their biological activity in particular, and help in building up the micro-flora and soil health in general.

In India, biofertilizers were brought under the regulatory purview of the Fertilizer (Inorganic, Organic or Mixed) (Control) Order (FCO), 1985, under the Union Ministry of Agriculture and Farmers' Welfare, in 2006. As of now, 11 biofertilizers are approved under FCO, which include nitrogen fixers and phosphate-solubilizing and potassium-mobilizing biofertilizers of bacterial or fungal nature. They are available in solid and liquid formulations. Government of India has initiated several schemes and programmes through which it promotes production and use of biofertilizers and organic fertilizers. These schemes include those aimed at farmers to promote organic and natural farming such as ParamparagatKrishiVikasYojana, Mission Organic Value Chain Development for North Eastern Region, National Food Security Mission and National Mission on Oilseeds and Oil Palm.

However, the sum total of funds spent on these schemes and programmes is dwarfed by the annual subsidy provided on chemical fertilizers. For example, the total organic farming practicing area covered under these schemes and programmes is only about 2.7 per cent of India's net sown area of 140.1 million hectare. Between 2018 and 2021, a sum of only Rs 994 crore was released for Paramparagat Krishi Vikas Yojana, Rs 416 crore for the Mission Organic Value Chain Development for North Eastern Region, and about Rs four crore for biofertilizers under the National Food Security Mission. Similarly, subsidy schemes aimed at supporting biofertilizer and organic fertilizer manufacturers and for laboratory infrastructure include the Capital Investment Subsidy Scheme (CISS), the Soil Health Management scheme, the Policy on Promotion of City Compost and the New National Biogas and Organic Manure Programme.

Biofertilizers - How they work:

- **Nutrient Fixation:**

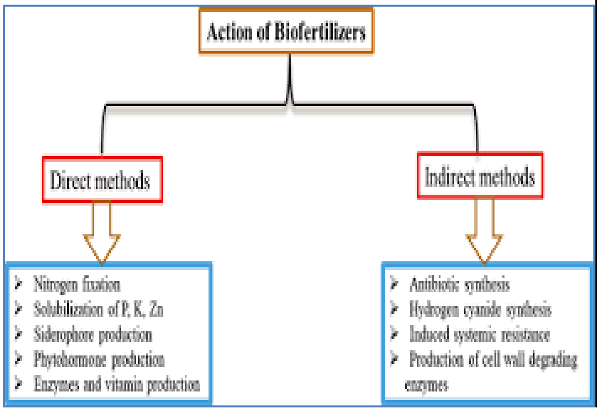
  Certain biofertilizers, like Rhizobium, form symbiotic relationships with plant roots, particularly in legumes, and fix atmospheric nitrogen, making it available to the plant.

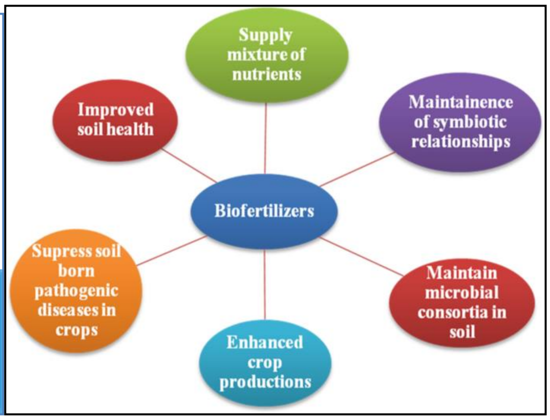
- **Nutrient Solubilization:**

  Others, like phosphate-solubilizing bacteria, convert insoluble forms of phosphorus into soluble forms that plants can readily absorb.

- **Hormone Production:**

  Some biofertilizers produce plant hormones like auxins and cytokinins, which stimulate root growth and overall plant development.





- **Organic Matter Decomposition:**

  Biofertilizers can also enhance the decomposition of organic matter in the soil, releasing nutrients for plant uptake.

Benefits of using biofertilizers:

- **Environmentally friendly:**

  Biofertilizers reduce the need for synthetic fertilizers, minimizing environmental pollution and promoting sustainable agriculture.

- **Cost-effective:**

  Biofertilizers can be a more affordable option compared to chemical fertilizers, especially in the long run.

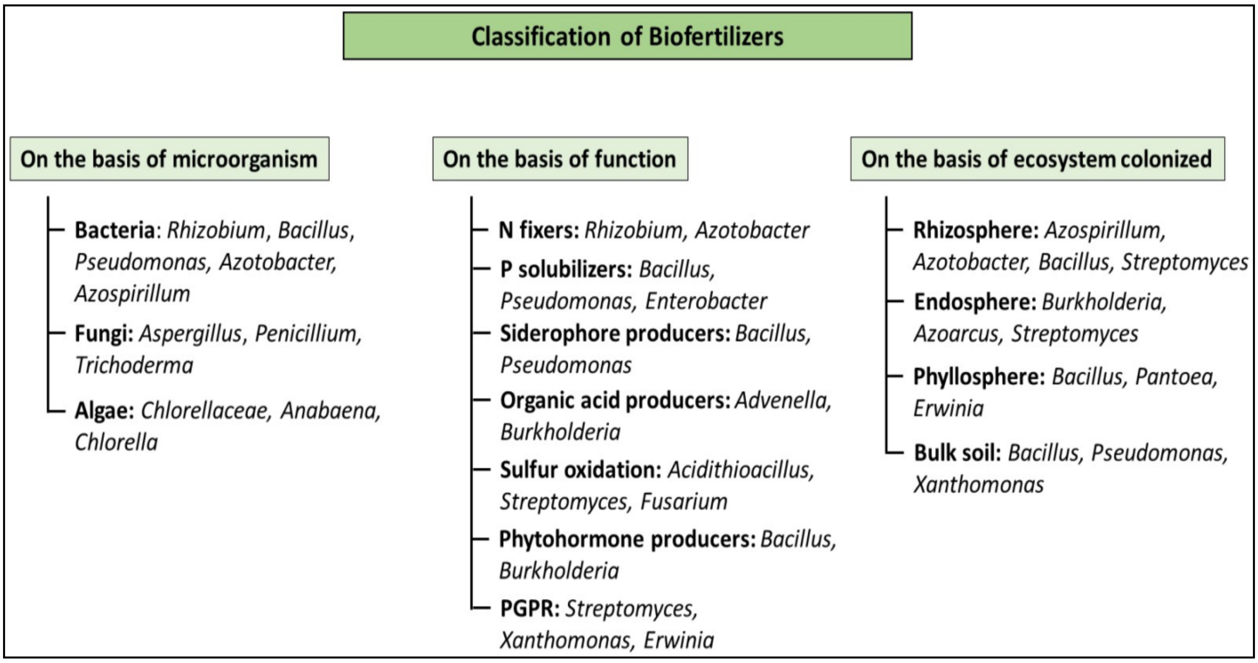
- **Improved soil health:**

  They enhance soil fertility, improve soil structure, and increase water-holding capacity.

- **Increased crop yields:**

  By enhancing nutrient availability and promoting plant growth, biofertilizers can lead to increased crop yields.

Biofertilizers can be classified based on several factors, including the type of microorganism, the nutrient they help deliver, and their mechanism of action. The microbial inoculants-based biofertilizers can be classified on the basis of microorganism, on the basis of function and on the basis of ecosystem colonized and also for plant growth promoting activity.



Biofertilizers can be classified based on their primary function in plant nutrition into several categories, including nitrogen-fixing, phosphate-solubilizing, potassium-solubilizing, and plant growth-promoting rhizobacteria (PGPR). These categories represent different microbial groups and their respective roles in enhancing nutrient availability and plant growth.

1. Nitrogen-Fixing Biofertilizers:

These biofertilizers contain microorganisms that convert atmospheric nitrogen into a form usable by plants, primarily through symbiotic or non-symbiotic relationships.

Examples include:

- **Rhizobium**:

Rhizobium is a genus of Gram-negative soil bacteria that fix nitrogen. *Rhizobium* species form an endosymbiotic nitrogen-fixing association with roots of (primarily) legumes and other flowering plants.The bacteria colonize plant cells to form root nodules, where they convert atmospheric nitrogen into ammonia using the enzyme nitrogenase. The ammonia is shared with the host plant in the form of organic nitrogenous compounds such as glutamine or ureides. The plant, in turn, provides the bacteria with organic compounds made by photosynthesis. This mutually beneficial relationship is true of all of the rhizobia, of which the genus *Rhizobium* is a typical example. *Rhizobium* is also capable of solubilizing phosphate.

- **Azotobacter:**

Azotobacter is a genus of usually motile, oval or spherical bacteria that form thick-walled cysts (and also has hard crust) and may produce large quantities of capsular slime. They are aerobic, free-living soil microbes that play an important role in the nitrogen cycle in nature, binding atmospheric nitrogen, which is inaccessible to plants, and releasing it in the form of ammonium ions into the soil (nitrogen fixation). In addition to being a model organism for studying diazotrophs, it is used by humans for the production of biofertilizers, food additives, and some biopolymers. *Azotobacter* species are Gram-negative bacteria found in neutral and alkaline soils, in water, and in association with some plants.

- **Azospirillum:**

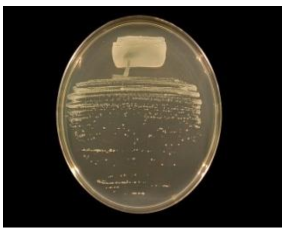
Azospirillum is a Gram-negative, microaerophilic, non-fermentative and nitrogen-fixing bacterial genus from the family of Rhodospirillaceae. It is a free-living bacterium that can also fix nitrogen in the soil. Growth of Azospirillum is possible between 5 °C and 42 °C and in substrates with a pH of 5 to 9, with optimal growth occurring around 30 °C and 7 pH. Azospirillum promote plant growth through a variety of mechanisms. Many Azospirillum excrete plant hormones that alter how the roots of plants grow. Affected roots frequently grow more branches and fine root hairs, which may help the plants acquire water and nutrients more efficiently. In addition to these changes, Azospirillum can also alter the forms of plant nutrients such as nitrogen and phosphorus to make them more available to plants. However, how much nitrogen Azospirillum contribute to crop plants via biological fixation is debated. Azospirillum also make antioxidants that protect the plant roots from stresses due to drought and flooding. Plant growth can also be promoted indirectly by Azospirillum reducing plant disease. Azospirillum competes with pathogens on the roots for space and for trace nutrients such as iron. The plants' immune systems can also be primed by Azospirillum to resist attack by pathogens, a process known as induced systemic resistance.

- **Cyanobacteria (Blue-Green Algae):**

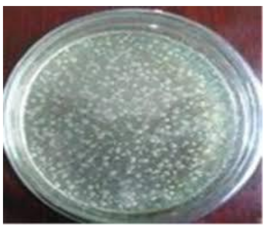
Cyanobacteria are a group of autotrophic gram-negative bacteria of the phylum Cyanobacteriota that can obtain biological energy via oxygenic photosynthesis. The name "cyanobacteria" refers to their bluish green color, which forms the basis of cyanobacteria's informal common name, blue-green algae. Some species, like Nostoc, can fix nitrogen and are used as biofertilizers, often in association with plants like Azolla.

Nitrogen-Fixing Biofertilizers

Rhizobium

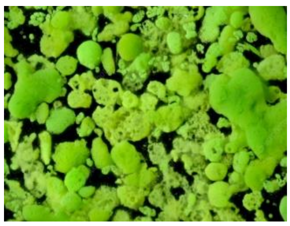


Azotobacter



Azospirillum

Cyanobacteria (Blue-Green Algae)



2. Phosphate-Solubilizing Biofertilizers:

Phosphate-solubilizing microorganisms (PSMs) have the ability to transform the insoluble P forms into soluble forms, which can function as biofertilizers by increasing the soluble P content in soil. The use of P biofertilizers is an eco-friendly approach that can be used to treat the problem of infertile soil.

Examples include:

- **Bacillus:** A genus of bacteria known for its ability to solubilize phosphate. These bacteria convert insoluble forms of phosphate into soluble forms that plants can readily absorb, thus improving plant growth and yield while potentially reducing the need for chemical fertilizers. By solubilizing phosphate, Bacillus PSB ensures that plants have access to this vital nutrient, leading to better growth and higher yields.
- **Pseudomonas:** Pseudomonas species are known to be effective phosphate-solubilizing microorganisms (PSMs) used as biofertilizers. They solubilize insoluble phosphorus in the soil, making it available for plant uptake, which can significantly improve plant growth and yield. These bacteria achieve this through the production of organic acids and enzymes like phosphatases.
- **Aspergillus:** Aspergillus species are known phosphate-solubilizing microorganisms (PSM) that can be used as biofertilizers. These fungi can convert insoluble forms of phosphorus in the soil into soluble forms that plants can readily absorb, contributing to improved plant growth and yield. Several Aspergillus species, including *A. niger, A. flavus,* and *A. tubingensis*, have demonstrated the ability to solubilize various phosphate compounds.

Phosphate-Solubilizing Biofertilizers

Bacillus ***Pseudomonas*** ***Aspergillus***

3. Potassium releasing biofertilizers:

Potassium-releasing biofertilizers utilize beneficial microorganisms, primarily bacteria, to convert insoluble potassium compounds in the soil into a soluble form that plants can readily absorb. These microorganisms, often referred to as potassium solubilizing bacteria (KSB), play a crucial role in making potassium, an essential nutrient, available to plants, thus potentially reducing the need for synthetic potassium fertilizers. Some studies suggest that potassium-solubilizing bacteria can also help plants better tolerate environmental stresses, such as drought or salinity.

Examples include:

- **Bacillus mucilaginosus**:

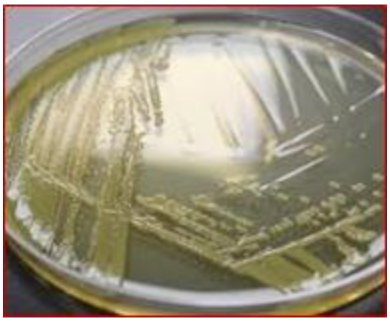
Bacillus circulans, Bacillus edaphicus, Bacillus urkholderia, A. ferrooxidans, Arthrobacter sp., *Enterobacterhormaechei*, and *Paenibacillusglucanolyticus* are some examples of potassium solubilizing bacteria.

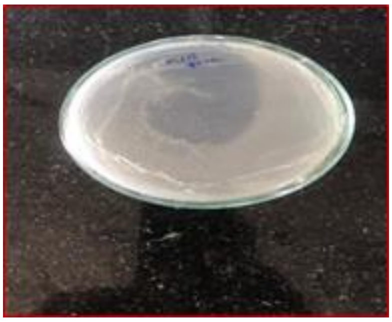
- **Burkholderiacepacia**:

Delftiaacidovorans, *Paenibacillusmacerans*, *Pantoeaagglomerans*, *Pseudomonas* spp., *Bacillus* spp., and *Azospirillum brasilense* are also mentioned in relation to potassium solubilization.

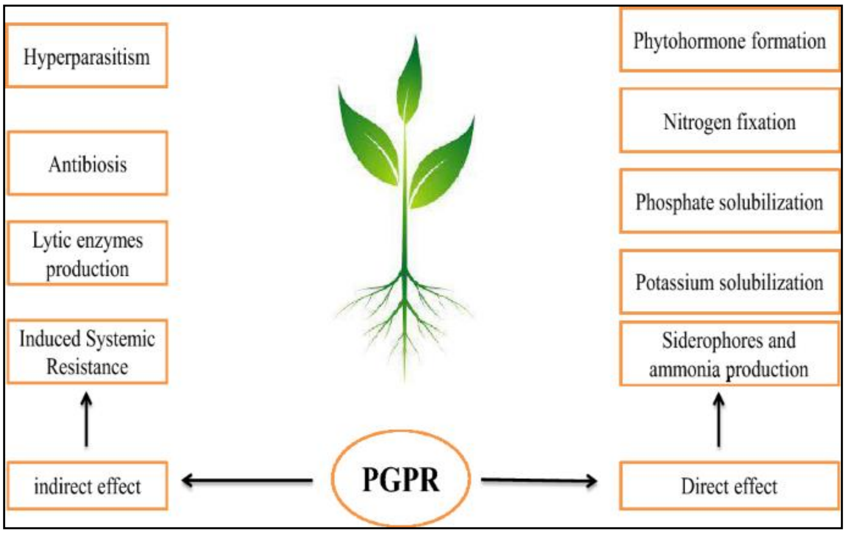
Potassium-releasing biofertilizers

Burkholderiacepacia ***Bacillus mucilaginosus***





4. Plant Growth-Promoting Rhizobacteria (PGPR):



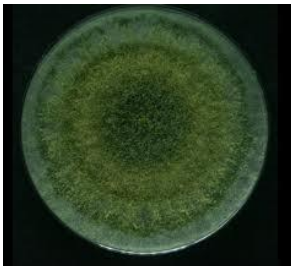
Plant Growth Promoting Rhizobacteria (PGPR) are a group of bacteria that live in the soil and enhance plant growth and health. PGPR can make essential nutrients like phosphorus and nitrogen more available to plants by solubilizing them from unavailable forms or fixing atmospheric nitrogen. Some PGPR produce plant hormones like auxins, cytokinins, and gibberellins, which regulate plant growth and development. PGPR can also produce siderophores, which are molecules that bind iron and make it more accessible to plants. In addition, they through various mechanisms, achieve biocontrol of pathogens. PGPR offer a sustainable alternative to synthetic fertilizers and pesticides, promoting plant growth and reducing the need for harmful chemicals.

Examples include:

- **Pseudomonas:** Pseudomonas are a group of bacteria known to enhance plant growth and health. They achieve this through various mechanisms, including producing phytohormones, solubilizing nutrients, and suppressing plant pathogens. Pseudomonas species are particularly well-studied within the PGPR group due to their diverse beneficial effects on plants. Often used as PGPR due to their ability to produce growth-promoting substances and siderophores.
- **Bacillus:** *Bacillus megaterium* that can enhance plant growth and stress tolerance and can achieve this through various mechanisms, including producing phytohormones, fixing nitrogen, solubilizing phosphates, and producing siderophores. Additionally, it can induce systemic resistance in plants, making them more resilient to pathogens and abiotic stresses.
- **Trichoderma:** Trichoderma is a fungus that can also promote plant growth and act as a biocontrol agent against plant pathogens (Trichoderma asperellum and Trichoderma harzianum). Trichoderma also solubulizesunavaialbephosphates to available phospahtyes to palnt and also acts as good organic matter decomposer.

Plant Growth-Promoting Rhizobacteria (PGPR)

Pseudomonas ***Bacillus*** ***Trichoderma***



5. Mycorrhizal Fungi:

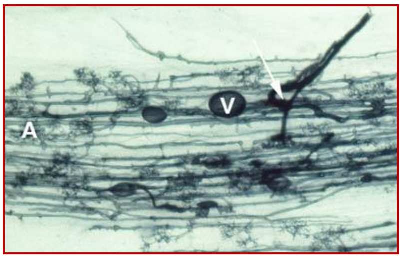
Mycorrhizal fungi are fungi that form a symbiotic relationship with plant roots, enhancing the plant's ability to absorb nutrients and water from the soil. This beneficial association, known as mycorrhiza, allows the fungus to receive sugars and other compounds from the plant, while the plant benefits from the fungus's enhanced nutrient uptake capabilities. The fungal network also helps plants absorb water more efficiently, making them more resilient to drought conditions. Some mycorrhizal fungi can protect plants from soil-borne diseases and harmful pathogens. The symbiotic relationship can also increase a plant's tolerance to various abiotic stresses, such as drought, salinity, and heavy metal toxicity.

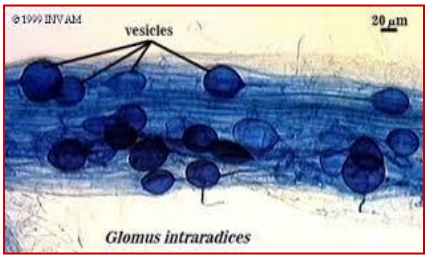
Examples include:

- **Vesicular-Arbuscular Mycorrhizae (VAM):** Vesicular-arbuscular mycorrhizae (VAM), also known as arbuscular mycorrhizae (AM), are a type of mycorrhizal fungi that forms a symbiotic relationship with the roots of most terrestrial plants. These fungi penetrate the plant's root cells, creating arbuscules (nutrient exchange structures) and vesicles (nutrient storage structures). This association is crucial for plant health and growth, particularly in nutrient-poor soils.
- **Glomus:** A common genus of VAM fungi. Glomus mycorrhiza refers to a symbiotic relationship between plant roots and a specific type of fungus, belonging to the genus Glomus, within the arbuscular mycorrhizal (AM) fungi group. This association is beneficial for both the plant and the fungus, as the fungus helps the plant absorb water and nutrients from the soil, while the plant provides the fungus with sugars produced through photosynthesis.

Mycorrhizal Fungi

Vesicular-Arbuscular Mycorrhizae (VAM)	**Glomus**	**Plant root and Mycorrhizal Fungi association**





Advantages of Mycorrhizal fungi

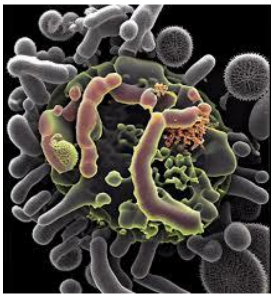
1. Increased Nutrient Uptake: Fungal hyphae extend beyond the root zone, reaching nutrients that cannot be accessed by roots alone. The best nutrient uptake is particularly efficient in phosphorus, as this nutrient is immobile in soil.
2. Increased Water Absorption Hyphal networks improve the access of a plant to water in soil during drought conditions.
3. Resistance to Diseases- Mycorrhizal fungi form a protective barrier around roots to protect them from soil-borne pathogens.
4. Stress Resistance- Help plants tolerate stress factors such as salinity, heavy metals, and drought.
5. Improved Soil Structure: Fungal hyphae exude chemicals such as glomalin, which agglutinates soil particles, improving porosity and aeration.

4. Other Biofertilizers:

- **Sulfur Oxidizers:** Sulfur oxidizers are microorganisms, primarily bacteria and some archaea, that obtain energy by oxidizing reduced sulfur compounds, such as sulfide, thiosulfate, and elemental sulfur, into sulfate. This process is a crucial part of the sulfur cycle in various ecosystems and can be used in biofertilizers. Microbes like Thiobacillus that oxidize elemental sulfur to sulfates, making it available to plants.

- **Zinc Solubilizers:** Zinc solubilizing microorganisms solubilize zinc through various mechanisms, one of which is acidification. These microbes produce organic acids in soil which sequester the zinc cations and decrease the pH of the nearby soil. Zn-solubilizing rhizobacteria are a useful alternative to enhance zinc availability in the soil. Several bacteria including Acinetobacter, Bacillus sp., Pseudomonas sp., Rhizobium, Azospirillum, Burkholderiacenocepacia, Serratialiquefaciens and S. marcescens, Cyanobacteria have been reported to solubilize zinc.
- **Composting Accelerators:** Compost accelerators are microbial products designed to speed up the composting process by introducing beneficial bacteria and fungi that break down organic matter. These accelerators help initiate and enhance decomposition, often by providing nutrients that the microorganisms need to thrive. Fungi and bacteria that help decompose organic matter in compost piles.

Sulfur Oxidizers **Zinc Solubilizers** **Composting Accelerators**



Application Methods of Biofertilizers (Powder/ Solid Form)

Biofertilizers can be applied to crops using various methods, including seed treatment, seedling dipping, and soil application. These methods aim to introduce beneficial microorganisms to the soil or directly to the plant, enhancing nutrient availability and promoting growth.

Seed Treatment

About 200 g of biofertiliser is required to treat 10-14 kg of seed. One packet of 200 g may be suspended approximately in 400 ml of adhesive such as rice gruel or 10% jaggary solution and mixed thoroughly. This mixture is to be added to the seeds and mixed with hands to obtain uniform coating on each and every seed. The seeds should be spread in shade for a duration of 10-15 minutes and then the sowing should be taken up immediately.

Set Treatment

A culture suspension should be prepared by mixing one kg of culture in 50-60 liters of water. The cut pieces of planting material required for one acre should be kept immersed in the suspension for 10-15 minutes. Then these cut pieces should be taken out and allowed to dry for 10-15 minutes before planting. Cut pieces are applicable for crops like sugarcane, potato etc.

Seedling Dip

Seedling treatment is recommended for tomato, chilli, onion, fruit plant seedlings etc. A suspension is to be prepared by mixing one kg of culture in 10-15 liters of water. The seedlings required for one acre should be made into small bundles and kept in the suspension for 15-20 minutes. The treated seedlings should be transplanted immediately. Generally, the ratio of inoculants and water should be 1: 10 approximately i.e., one kg packet in 10 liters of water.

Soil Application

About 2 kg of biofertilizer is mixed with 100 kg of soil/compost/castor cake. The same has to be broadcasted in one acre of land either at sowing time or 24 hours before sowing. In case of fruit crops, they are to be applied with organic manures in the basins around the trunk of the plant.

Liquid Biofertilizers:

To avoid problems in carrier-based inoculants and to increase the quality and shelf life of microbial inoculants, Acharya NG Ranga Agrcultural University developed a liquid formulation for Rhizobium, Azospirillum, Azotobacter, Phopshate solubilizing Bacteria (PSB) and Potash releasing bacteria.

Benefits:

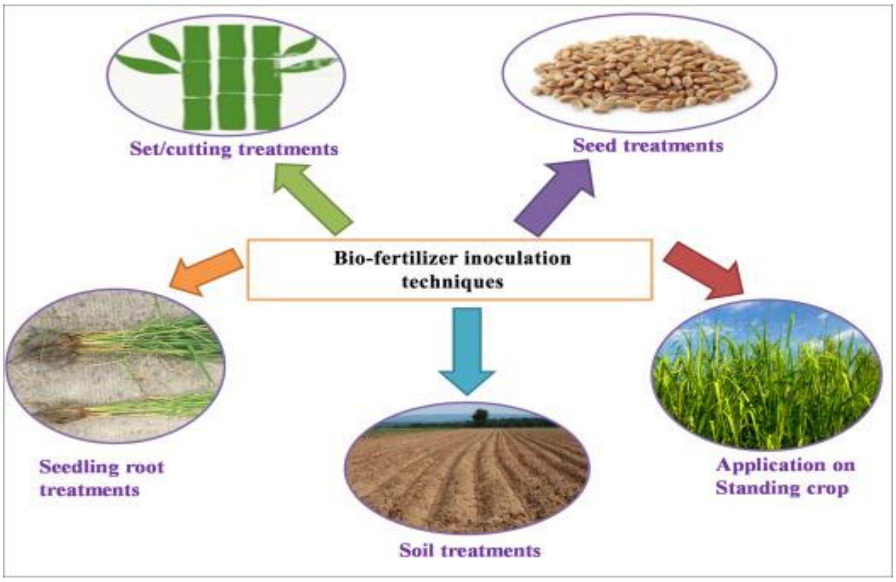
- Liquid bio fertilizers have got more shelf life
- One ml of bio fertilizer contains more than 10^8 cells at the end of expiry date with zero contamination.
- Easy to apply for larger areas.
- Easy establishment in the crop root zone.
- Tolerant to high soil temperatures and other stress conditions.
- This technology ensures proper delivery of biofertilizer organism to the root zone
- Enhances the crop growth and yield.
- In organic farming, this biofertilizer technology will be one of the major inputs for obtaining sustainable crop yields.

Application Method:

- **Seed Treatment**: For one Kg of the seed, 5-6 ml of liquid biofertilizer should be mixed with equivalent quantity of 10% starch solution or 10% jaggary solution and coat the mixture uniformly on the seed and expose for shade dry for 10 minutes before sowing.

- **Seedling Dip** (Azopsirillum only): 250 ml of liquid biofertilizer of Azospirillum should be mixed with 70 lit of water and the root portion of the seedlings should be dipped for 10 minutes just before transplanting (most widely applicable for all nursery raised crops).
- **Soil Application**: 500 ml of liquid biofertilizer of each organism can be used for one acre of main field. All the Inoculants should be diluted with 5 litres of water and then mixed with 100 kg of powdered farm yard manure or vermicompost or any other compost just before application. This mixture should be applied at the time seed sowing/transplantation preferably in the furrows below the seed surface. At any cost this application should be completed before the first inter-culturing operation. Immediately after application of biofertilizers light irrigation is always preferable.
- **Crops with Drip Irrigation Facility**: The liquid biofertilizer should be mixed at the rate of 500 ml of each organism per acre in drip tank and release within 10-15 days after transplantation/ sowing.

Application methods of biofertilizers

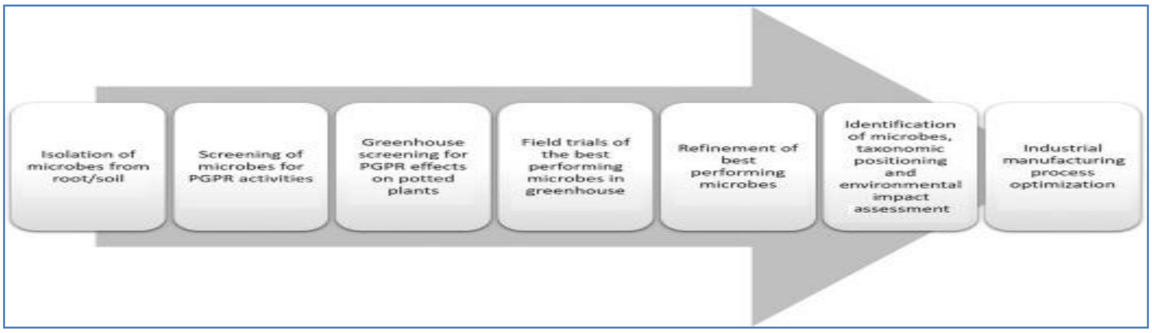


Manufacturing process:

The manufacture of biofertilizers requires a standardized laboratory and equipment as well as other production facilities such as fermenters, culture medium tank, fermenter assembly, autoclaves, boiler, broth dispensers for sterilization, demineralizing plant, air compressor, etc.

Lab scale Manufacturing process:

The first step in the development of a potent biofertilizer begins at the lab scale with isolation of an array of microbes and identifying their potential as plant growth promoters. The process involved in recognizing microbes for their development into biofertilizers has been illustrated in the following diagram.

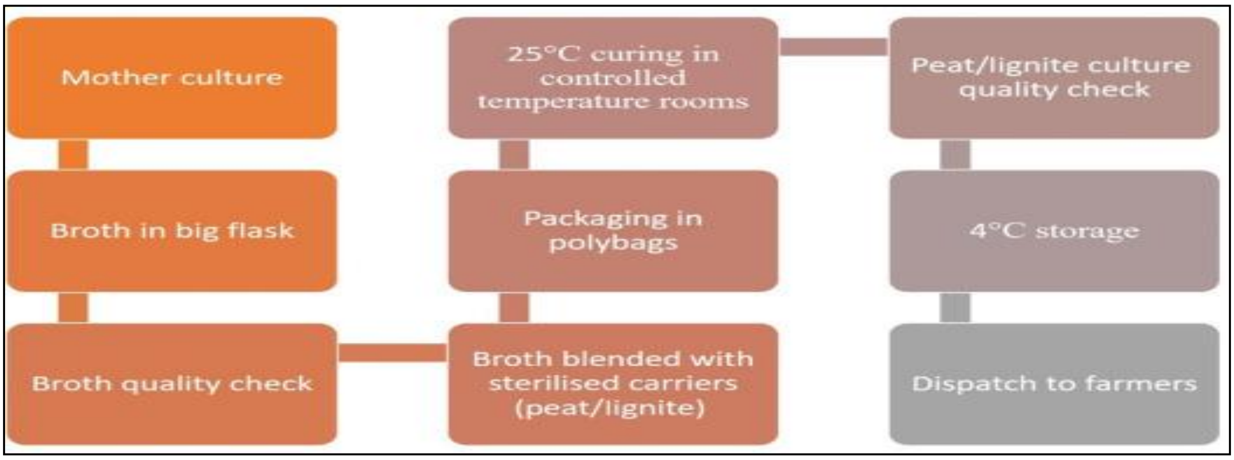


A typical journey of a microbe from the lab to the industrial manufacturing unit

Industrial scale Manufacturing process:

The industrial scale manufacturing of biofertilizers involves the fermentation mass production process and formulation procedure. Solid-state fermentation and submerged fermentation are the two main types of fermentation used to produce biofertilizers (Yadav and Chandra, 2014).

Commercial biofertilizers are mainly liquid or solid, based on the property and efficacy of the bacteria/rhizobacteria involved. Recently, cell free fermentation broth filtrates have also been developed as the bacterial culture extracts are enriched with antibiotics, lytic enzymes, toxins, and siderophores. Liquid formulations are microbial cultures in water or liquids like oil or polymer to enhance stability and dispersion capacity. Solid formulations involve carriers which can be organic or inorganic like peat, perlite, vermiculite, calcium sulfate, and rock phosphate. Such formulations are granular or powdery in form depending upon the particle size or application method. With the advancement in technology, solid-state formulations are now being developed as polysaccharide-immobilized inoculants and solid-state fermentation products. Gel cell immobilized formulations are the next generation biofertilizer technology under research and development.The microbial count of the inoculants must be checked at the time of manufacturing. The viable cell count in the inoculants should be maintained as per ISI specifications.



Process flow chart for production of biofertilizers in a manufacturing unit

Since a bio-fertilizer is technically living, it can symbiotically associate with plant roots. Involved microorganisms could readily and safely convert complex organic material into simple compounds, so that they are easily taken up by the plants. Microorganism function is in long duration, causing improvement of the soil fertility. It maintains the natural habitat of the soil. It increases crop yield by 20-30%, replaces chemical nitrogen and phosphorus by 30%, and stimulates plant growth. It can also provide protection against drought and some soil-borne diseases.

Biofertilizer Production Units, Regional Agricultural Research Station, Anakapalle (Andhra Pradesh, India)

Lignite based (Powder) Biofertilizer Production Unit

Liquid Biofertilizer Production Unit

Biofertilizer production centers at ANGRAU

1. Regional Agricultural Research Station, Tirupati
2. Regional Agricultural Research Station, Anakapalli
3. Agricultural Research Station, Amaravathi
4. Agricultural Research Station, Utukur (Kadapa)

Table 1: Production Capacity of Biofertilizer units at ANGRAU

S. No	Name of the Production Unit	Production capacity (MT)	
		Solid (MT)	Liquid (MT)
1	Regional Agricultural Research Station, Tirupati	200	200
2	Regional Agricultural Research Station, Anakapalli	100	100
3	Agricultural Research Station, Amaravathi	250	200
4	Agricultural Research Station, Utukur (Kadapa)	100	100
	Total	**650**	**600**

Table 2: Anticipated Demand of Biofertilizers for economical and sustainable crop production for total cultivable area in Andhra Pradesh

Total cultivable area in Andhra Pradesh(ha)	61,89,298
Total expenditure on fertilizers (Rs)	Rs.33,00,75,26,234
Total estimated expenditure on biofertilizers	Rs.6,76,49,02,714
Expenditure per hactare	
Expenditure on fertilizers	Rs.10,665
Total expenditure on biofertilizers	Rs. 1,156
Saving of 25% of expenditure on Chemical fertilizers	Rs. 2,666

In essence, Biofertilizers are live microbial products which do not contain any nutrients. The micro-organisms present in the bio-fertilizer ensure availability of nutrients from non-available form present within soil and air to available form which plants can uptake. Bio-fertilizers can improve crop yields by 10-25% and supplement costly chemical fertilizers (N, P) by nearly 20-25% in most of the cases when used along with chemical fertilizers without any reduction in production.

Eleven (11) biofertilizers *viz.*, *Rhizobium*, *Azotobacto*r, *Azospirillu*m, Phosphate Solubilising Bacteria PSB), Mycorrhizal Biofertilizers, Potassium Mobilizing Biofertilizers (KMB), Zinc Solubilizing Biofertilizers (ZSB) *Acetobacte*r, Carrier Based Consortia, Liquid Consortia and Phosphate Solubilising Fungus (PSF) have been notified and included **into** the Fertilizer (Control) Order, 1985. The quality standards of these bio-fertilizers have been specified under the FCO, 1985. (Ministry of Agriculture & Farmers Welfare Postedon Use of Biofertilizers Dated: 07 FEB 2023 by PIB Delhi).

Table 3: Consolidated anticipated demand of biofertilizers for economical and sustainable crop production for major crops in Andhra Pradesh

Crops	Total area (Lakh ha)	Quantity (MT)	Biofertilizers requirement for major crops in Andhra Pradesh								Total Expenditu re on fertilizers (Rs in Cr.)	Total expendi ture saved 25% reducti on) (Rs in Cr.)	Amoun t saved on fertilize rs upon use of biofertilizers (Rs in Cr.)	Amount saved on fertilizers upon use of biofertilizers per acre (Rs)
			Nitrogen Biofertilizers		Phosphate Biofertilizers		Potassium Biofertilizers		Total Biofertilizers					
			Expenditure on Biofertilizers (Rs in Cr)	Quantity (MT)	Expenditure on Biofertilizers (Rs in Cr)	Quantity (MT)	Expenditure on Biofertilizers (Rs in Cr)	Quantity (MT)	Expenditure on Biofertilizers (Rs in Cr)	Total Expenditure on Chemical Fertilizers / ha (Rs.)				
Rice	25.52	3189.49	95.68	3189.49	95.68	3189.49	95.685	9568.5	287.0	13000	3317.06	829.27	542.21	2125
Maize	3.01	376.77	11.30	376.77	11.30	376.77	11.303	1130.3	33.9	12000	361.70	90.42	56.52	1875
Sorghum	4.10	512.70	15.38	512.70	15.38	512.70	15.381	1538.1	46.1	8000	328.12	82.03	35.89	875
Bajra	0.31	38.39	1.15	38.39	1.15	38.39	1.152	115.2	3.5	8000	24.57	6.14	2.69	875
Redgram	2.31	28.90	0.87	289.00	8.67	289.00	8.670	606.9	18.2	4200	97.10	24.28	6.07	262.5
Blackgram	3.65	109.45	3.28	456.03	13.68	456.03	13.681	1021.5	30.6	4000	145.93	36.48	5.84	160
Greengram	1.05	31.53	0.95	131.39	3.94	131.39	3.942	294.3	8.8	4000	42.05	10.51	1.68	160
Bengalgram	4.69	585.86	17.58	585.86	17.58	585.86	17.576	1757.6	52.7	10000	468.69	117.17	64.45	1375
Groundnut	8.69	1086.39	32.59	1086.39	32.59	1086.39	32.592	3259.2	97.8	11000	956.03	239.01	141.23	1625
Cotton	6.06	758.01	22.74	758.01	22.74	758.01	22.740	2274.0	68.2	9000	545.77	136.44	68.22	1125
Sugarcane	0.57	142.37	4.27	71.18	2.14	71.18	2.135	284.7	8.5	19000	108.20	27.05	18.51	3250
Total	**59.96**	**6859.85**	**205.80**	**7495.21**	**224.86**	**7495.21**	**224.856**	**21850.3**	**655.5**	**102200**	**6395.22**	**1598.80**	**943.30**	**1573.16**

Finally, biofertilizers offer a promising path towards more sustainable and environmentally friendly agricultural practices, promoting both healthy crops and a healthy planet.

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CATTLE FEED NUTRITION ENHANCES RESISTANCE AGAINST ECTOPARASITES IN CATTLE

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Abstract:

"The green grass sustains calves and calves sustain mankind."

Nedunthokai

Ectoparasitic infestation on cattle impacts adverse effect on the cattle health like productivity is causing economic losses. The improvement of nutritional quality such as adequate provision of proteins, energy, vitamins and minerals in order to strengthen the immune system of animals provokes natural defences against controlling parasites. Nutraceuticals and bioactive forages such as condensed tannin-rich plants offer natural alternatives for parasitic management. This chapter explores about the fundamentals of cattle feeding that includes types of rations, nutrient sources and its roles in supporting maintenance and production functions by integrating nutritional elements into an integrated parasitic management framework involves leveraging traditional medicinal plants, optimized nutritionand good husbandry practices to sustainable control parasites and promote animal welfare and productivity.

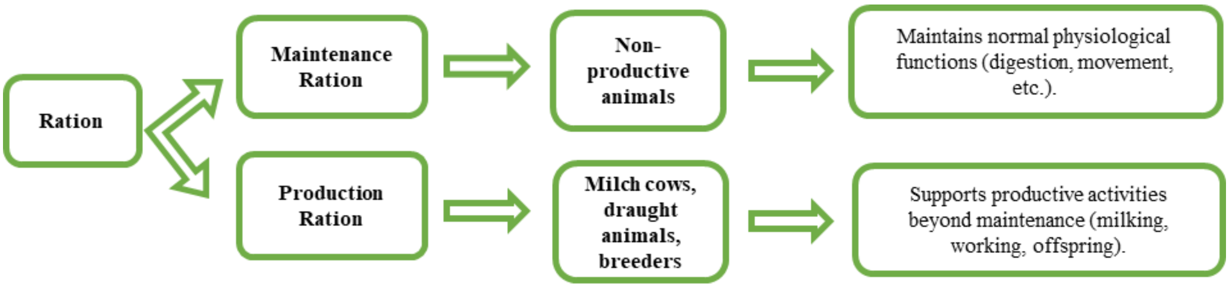
Introduction:

Livestock nutrition is fundamentally important for the health, productivity and sustainability of animal agriculture. Recent research findings suggest that providing nutrition with balanced diets that satisfy animal's physiological needs including protein, energy, water, fiber, minerals, and vitamins to support growth, reproduction and immune function. An example, a review on climate smart livestock nutrition emphasizes adapting diets to enhance thermal resilience in animals exposed to heat stress, optimizing bioenergetics for improved energy use and incorporating sustainable feed resources to mitigate climate impacts and maintain production efficiency (Fushai *et al.,* 2025). The study result shows nutrition acts as a key factor in both animal welfare and environmental sustainability. In addition, from a human nutrition perspective, livestock-derived foods provide highly bioavailable essential nutrients such as high-quality protein, vitamin B_{12}, preformed vitamin A, iron, zinc and calcium which are particularly critical during the first 1,000 days of lifefrom conception through the early toddler years (Alonso *et al.,* 2019). Research in low- and middle-income countries demonstrates that consumption of meat, milk and eggs correlates with improved micronutrient status and cognitive development among children, especially those who are malnourished or stunted (Alonso *et al.,* 2019). Supplementation trials have shown benefits of livestock foods in increasing nutrient levels critical for growth and brain development, like vitamin B_{12} and iron. Therefore, livestock nutrition has broad implications, it not only supports optimal animal performance and farm profitability but also contributes significantly to human nutrition and public health by supplying essential dietary nutrients, especially in vulnerable populations.

Feeding and Ration Basics

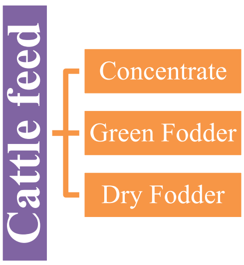
Feeding is the act of providing animals with a diet that supplies optimal nutrition for their health and productivity, ensuring they receive the nutrients necessary to support growth, reproduction and lactation. Ration refers to the total quantity of feed consumed by an animal in one day, designed to provide a balanced supply of essential nutrients such as carbohydrates, proteins, fats, vitamins and minerals (Erickson *et al.,* 2020). Proper feeding and ration formulation are essential for maximizing animal performance and well-being. esearch emphasizes the importance of nutrient balance and dry matter intake in dairy cattle, as these factors profoundly influence milk production and metabolic health (Martins *et al.,* 2022).

Chart 1: Types of Rations based on productivity



Types of Rations based on nature

Chart 2: Types of Rations based on nature



Concentrate:

Concentrate feed is a balanced mixture of essential nutrients including carbohydrates, proteins, fats, minerals and vitamins that are formulated to meet the nutritional requirements of cattle. It serves as a rich source of energy and nutrients that support maintenance, growth, and production functions such as milk yield. Concentrate feeds are provided in two main forms, they are powder and pellets. The powder form can be prepared at home by mixing individual feed ingredients according to the animal's nutritional needs, offering flexibility and costeffectiveness. Conversely, pelleted concentrates are industrially produced with uniform nutrient composition, which enhances feed intake, reduces wastage and improves digestibility. Both forms are critical in supplying nutrients that complement forage-based diets, thereby optimizing cattle health and productivity (Singh *et al.,* 2019).

A typical concentrate feed mixture for cattle, designed for a 100 kg batch, includes a balanced proportion of key nutrients to meet energy, protein, mineral and vitamin requirements. The composition generally consists of 35 to 50 kg of carbohydrates, which serve as the primary energy source. Oil cakes, such as groundnut or soybean cake, contribute 25 to 30 kg and provide a rich source of protein necessary for growth and lactation. Wheat bran, another important ingredient used for fibre and energy, is also included in the range of 25 to 30 kg. Minerals are added as a mineral mix, typically about 1.5 kg, to supply essential trace and macro minerals that support various physiological functions. Salt (sodium chloride) is included at around 500 grams to maintain electrolyte balance, while vitamins are added in a similar quantity to support metabolic and immune functions (Dairy Web, n.d.; Penn State Extension, 2023). This formulation ensures a comprehensive and balanced nutrient supply for optimal cattle performance.

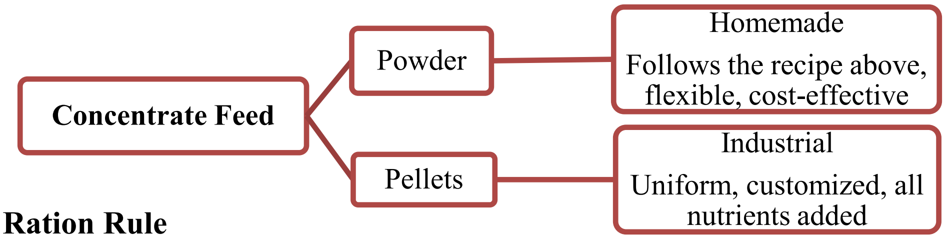
Table 1: Concentrate Feed Composition (Example for 100kg Mix)

Nutrient	Amount
Carbohydrates	35–50kg
Oil Cake	25–30kg
Wheat Bran	25–30kg
Mineral Mix	1.5kg
Salt (NaCl)	500
Vitamins	500g

Forms of Concentrate Feed

This structure helps ensure animals receive an optimal diet for maintenance and productivity, and it clarifies how to prepare and store feed for cattle health and safety.

Chart 3: Forms of Concentrate *Feed*



Production Ration Rule

The Production Ration Rule for concentrate feeding in dairy cows is supported by research demonstrating the relationship between concentrate intake and milk yield. A study on balanced concentrate feeds showed that adjusting feed levels according to milk production improves productivity, healthand reproductive performance in dairy cattle (Dhiraj *et al.,* 2019). Another experimental trial highlighted that supplementing dairy cows with varying proportions of carbohydrate sources in concentrates directly influenced feed intake and eating behaviour, thereby affecting milk production outcomes (Dickhoefer *et al.,* 2022). These studies emphasize the importance of tailoring concentrate feed quantities to milk output, validating the practice of providing 2.5 kg concentrate for 5 litres of milk, with an additional 1 kg for every 2.5-litre increase in milk yield.

Table 2: Practical Table

Milk Yield (litres/day)	Concentrate Feed (kg/day)	Calculation Method
5	2.5	Base (2.5kg)
7.5	3.5	2.5kg + 1kg
10	4.5	2.5kg + 1kg + 1kg
12.5	5.5	2.5kg + 1kg + 1kg + 1kg

**For any yield not matching these increments, use the 400g per litre rule (e.g., 8 litres × 0.4 = 3.2kg concentrate) **

This rule ensures cows get extra concentrate feed to support greater milk yield, preventing underfeeding or overfeeding, and maximizing milk production efficiency and animal health.

Storing Concentrate Feed

Proper storage of cattle concentrate feed is critical to maintain its quality and nutritional value. It is essential to keep the feed dry and ensure that the packaging does not come into contact with the floor or walls, as this helps prevent the uptake of moisture. Excess moisture in stored feed can lead to the growth of moulds, including the fungus *Aspergillus flavus*, which produces aflatoxinshighly toxic substances that pose serious health risks to animals. To minimize these risks, feeds should be stored in dry, well-ventilated areas, ideally in airtight containers elevated from the floor. Regular monitoring for signs of mould and implementing moisture control measures are effective ways to safeguard feed from contamination and spoilage (Farrelly Mitchell, 2025; Kreamer Feed, 2025).

Green Fodder

Green fodder primarily consists of high-water content (around 85%), with about 9% proteins and 6% other minerals. It is known to improve heat expulsion in animals by reducing the gain of direct and metabolic heat. Direct heat refers to heat from direct sunlight, which animals can experience while grazing, while metabolic heat is the heat produced internally during metabolic processes. Excess heat in animals is expelled through the homeostasis mechanism involving three types of heat loss: conduction, convection, and radiation. Green fodder helps animals by reducing heat gain and metabolic heat, aiding in temperature regulation. Nutritionally, green fodder has higher levels of calcium and phosphorus, which are essential minerals for animal health. The green fodder not only supports hydration due to its high-water content but also helps animals manage heat stress effectively while providing essential nutrients like calcium and phosphorus for growth and bone health, making it a valuable component in livestock feeding for improving overall animal well-being and productivity (Suma *et al.,* 2020). The production of green fodder requires approximately 10 cents of land per animal per year. Different types of fodder include grasses like Coimbatore grass (CO-1 to 7 varieties developed by TNAU), leguminous plants such as Stylo and tree leaves like neem leaves. For cultivation, about 16,000 fodder slips per acre are needed, with each slip containing two buds. The planting spacing is 50 cm by 50 cm for both row-to-row and plant-to-plant distances. Irrigation is given on the first and third days after planting and then once every 10 days. The first cutting of green fodder is at 75 days, followed by subsequent cuttings every 45 days, with a crop lifespan of around three years (Tamil Nadu Agriculture University). Other grasses include Para grass that thrives in waterlogged ditch areas, Guinea grass that grows well under shade and Kolukattai grass, which grows under various conditions and consumed at 15-25 kg per animal per day. Leguminous plants like Stylo are protein-rich shrubs; seeds are mixed with river soil, with cuttings taken at one foot height. Germination improves from 50-60% in the first year to 100% in the second year when seeds naturally fall and germinate. Suba Bull leguminous feed can be used both as green and dry feed but should not be fed individually for more than 15 days due to a toxin risk and is recommended at 3-4 kg per cow per day. Tree leaves are used as fodder in summer scarcity and should be dried before feeding. Spraying with 1% jaggery water or salt solution improves feed acceptance. These practices reflect scientific knowledge and practical recommendations for green fodder production in India, contributing to sustainable livestock nutrition and dairy productivity (Prakashkumar Rathod and Sreenath Dixit, 2019)

Cultivation pf Green Fodder

The production of green fodder requires about 10 cents of land per animal per year. Green fodder includes three main categories: grasses, leguminous plants, and tree leaves. Examples include Coimbatore grass varieties CO-1 to CO-7, Stylo (a leguminous shrub), and neem leaves as tree fodder. Coimbatore grass varieties, developed and distributed by Tamil Nadu Agricultural University (TNAU), are a popular choice for cultivation. For planting, approximately 16,000 fodder slips are needed per acre, with each slip containing two buds. The recommended spacing for planting is 50 cm by 50 cm between rows and plants. Irrigation is done on the first and third days after planting and then once every 10 days. The first cutting of green fodder occurs 75 days after planting, followed by subsequent harvests every 45 days. The grasses have a productive lifespan of about 3 years.

Other grass varieties include:

- Para grass, which grows in waterlogged ditch conditions.
- Guinea grass, a shade-tolerant ("shadow-loving") grass, grows well under tree canopies.
- Kolukattai grass, a hardy grass needing no special growing conditions, is consumed at the rate of 15-25 kg per animal per day.

For leguminous fodder:

- Stylo is a protein-rich shrub whose seeds should be mixed with river soil for planting. Cuttings should be taken at a height of about 1 foot. Germination is about 50-60% in the first year and reaches 100% in the second year as seeds drop and germinate naturally.
- Suba Bull, a leguminous feed usable as both green and dry feed, should not be fed individually for more than 15 days due to the risk of mimosin toxin formation. The recommended feeding rate is 3-4 kg per cow per day.

Tree leaves serve as green fodder during summer or when grasses are scarce. Common tree leaves can be fed at 1-2 kg per animal per day.

Role of Green Fodder

Moisture and Nutritional Content

Green fodder typically contains 85% water and about 9% protein, with the remaining 6% made up of minerals and other nutrients.

Thermal Regulation

Due to high moisture, green fodder helps animals regulate body temperature by promoting heat expulsion, which is crucial in hot climates.

Types of Heat

- **Direct Heat:** Absorbed from sunlight during grazing.
- **Metabolic Heat:** Produced internally during digestion and metabolism.

Mechanisms of Heat Loss

- **Conduction:** Transfer from body to cool surfaces.
- **Convection:** Heat carried away by moving air or water.
- **Radiation:** Emission of heat to surrounding cooler areas.

Mineral Benefits:

Green fodder is a significant source of calcium and phosphorus, key for bone health, reproduction and milk production.

Dry Fodder

Dry fodder commonly used includes paddy straw and rice straw, which contain about 98% dry matter and 2% moisture. Dry fodder primarily adds fibre to the animal's diet, with a recommended quantity of 5-7 kg per animal per day. Urea treatment of paddy straw enhances its nutritional value, for 100 kg of paddy straw, 4 kg of urea is mixed in 64 Liters of water and sprayed onto the straw, which is then sealed airtight for 21 days. This treatment breaks the bonds between cellulose, making the fodder more digestible. However, calves below 6 months should not be fed urea-treated straw due to potential toxicity.

Nutrient Sources and their Roles

- Carbohydrates serve as the main energy source for animals and are mainly found in cereals such as maize, sorghum, and ragi. They provide readily available energy required for bodily functions, growth, and production.
- Proteins are essential for growth, tissue repair, and maintenance of body functions. They are commonly supplied through oilseed cakes like gingelly (sesame), groundnut, cottonseed, and soybean cakes. These protein sources vary in composition; for example, expeller oil cakes still contain residual oil, while non-expeller types are defatted. Studies show that oilseed cakes are rich in protein (ranging from 40-50%) and possess a balanced amino acid profile crucial for animal health and production (Sharvary *et al.,* 2024). Soybean cake is particularly notable for its high protein concentration and digestibility compared to other oilseed cakes.
- Brands such as de-oiled rice bran and wheat bran provide fibre, which supports rumen function and digestive health. Fiber is integral for maintaining optimal gut motility and microbiota balance.
- Vitamins, though required in small amounts, play indispensable roles in metabolic and enzymatic functions. Optimized inclusion of vitamins ensures enzyme activities and immune responses are maintained.
- Antibiotics like tetracycline are sometimes given to calves to support health, by preventing or treating infections during vulnerable early growth stages.

- Minerals, required only in trace amounts, are critical for bone formation, enzyme activation, nerve function, and overall metabolism. Deficiencies or imbalances can lead to growth retardation, reproductive inefficiencies, and disease susceptibility.

Table 3: Minerals and their role

Mineral	Function
Calcium	Milk production, bone development
Phosphorus	Milk production
Zinc	Digestion (as cofactor)
Iron	Reproduction, blood
Iodine	Reproduction, hormones
Selenium	Reproduction
Sulphur	Hair development, synthesis of sulphur-containing amino acids
Copper & Sulphur	Prevents alopecia (notably in sheep)

Steps for Effective Cattle Feeding

Individual Feeding Preferred

Group feeding is not recommended, as it can lead to competition, uneven intake, and dominance issues among animals. Individual feeding ensures each cow receives its appropriate ration based on milk yield, physiological status, and body weight.

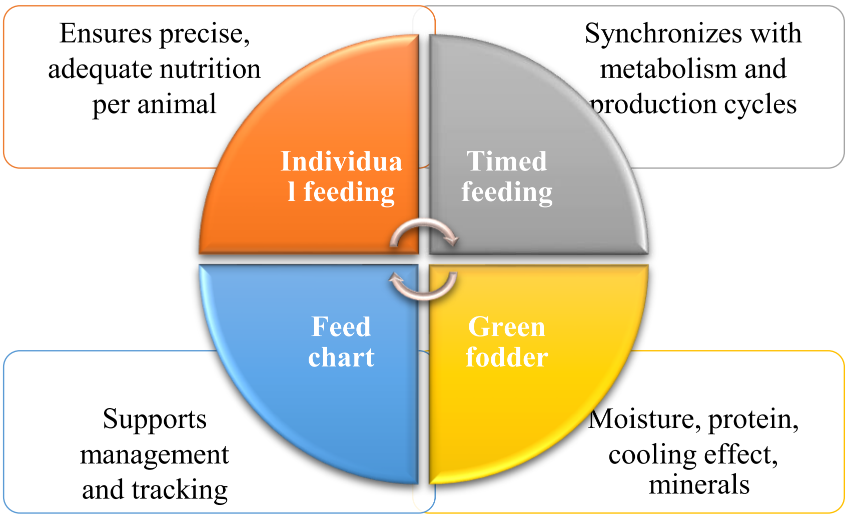
Timing

Feed should be offered 30 minutes to 1 hour before milking or exercise. This supports optimal digestion and availability of nutrients for milk production or exertion.

Use of a Feed Chart

Preparing and following a feed chart ensures consistency, allows for precise rationing, and facilitates record-keeping of intake and animal response.

Chart 4. Steps for Effective Cattle Feeding



By following these practices, dairy managers ensure efficient, targeted nutrition and thermal comfort, which together improve productivity and animal welfare.

Impact of parasites on cattle

Ectoparasites in cattleespecially ticks, lice, fliesand mitessignificantly depress productivity by reducing weight gain, causing cumulative blood loss and stress, and transmitting multiple diseases that magnify direct and indirect losses across beef and dairy systems (Byford *et al.,* 1992). Ectoparasite feeding and irritation lower intake and feed efficiency, while vector-borne transmission of pathogens compounds impacts through clinical and subclinical disease, treatment costs, and occasional mortality (Strydom *et al.,* 2023). Physiological stress responsesincluding altered energy balance, elevated cortisol, changes in thermos physiology, and reduced nitrogen retentiontranslate into poorer performance even without overt disease. Heavy tick burdens, horn fly attacks, louse infestations, and mange from mites contribute to anaemia, pruritus, dermatitis, and immune modulation, with evidence that fly-free or effectively treated cattle gain markedly more weight than infested cohorts, and that youngstock suffer measurable liveweight penalties under louse pressure (Narladkar *et al.,* 2018). The infestation of hematophagous flies causes irritation, blood loss and behavioural disturbances which impair cattle health and productivity (Yaswanthkumar *et al.,* 2024). Ticks are proven vectors of babesiosis, theileriosis, and anaplasmosis, while flies facilitate bacterial, viral, ocular, and skin diseases; mites depress feed conversion and milk output, and lice interrupt feeding through pruritus and blood loss (Muhamad *et al.,* 2021).

The economic consequences of ectoparasites in cattle are substantial, reaching billions of US dollars annually when considering lost weight gain, reduced milk yield, mortality, and control expenditures, with widespread global exposure ensuring that even small per-animal losses aggregate into major national burdens. For instance, Brazil alone incurs estimated losses exceeding USD 13.9 billion annually due to internal and external parasites, including USD 3.24 billion attributed to cattle ticks and USD 2.56 billion to horn flies. Converting these to Indian Rupees (INR) using an approximate exchange rate of 1 USD = 83 INR (as of August 2025), the total loss in Brazil translates to about INR 1,154 billion (or 1.15 trillion INR) annually, with cattle tick losses around INR 269 billion and horn fly losses about INR 212 billion (Strydom *et al.,* 2023). Integrated parasite management based on routine monitoring, targeted treatments, strategic timing, and exposure reduction is essential to safeguarding productivity, animal welfare, and farm profitability. Effective control of ectoparasites yields notable per-head productivity gains and national-level economic savings, supporting vigilance even in regions with lower tick burdens but ongoing vector risks. This combined approach prevents cascading productivity losses and underpins sustainable cattle production worldwide (Grisi *et al.,* 2014; Kuchi and Aki, 2020).

Nutritional Approach

A nutritional approach to controlling ectoparasites in cattle focuses on strengthening the animal's immune system, resilience, and natural defence mechanisms, thereby reducing reliance on chemical treatments that often lead to resistance and environmental concerns. Improved nutrition, particularly adequate amounts of proteins, energy, vitamins (A, E) and minerals (zinc, selenium) support skin integrity, enhances inflammatory and immune responses and promotes wound healing from parasite-induced lesions. Research shows that poor nutrition exacerbates the negative impacts of tick infestations by weakening metabolic and growth functionswhereas highquality diets can decrease tick burden and improve the host's resistance to parasite development. This approach enhances physiological resilience by reducing stress hormones and improving nutrient utilization, allowing cattle to better withstand infestation pressure and maintain productivity. Integrating nutritional strategies with other control measures offers a sustainable pathway for managing ectoparasites by improving host health and reducing the frequency of chemical interventionswhich ultimately benefits animal welfare, reduces production losses and mitigates environmental impact (Abd-Elrahman et al.,2025; Adalberto*et al.,* 2020; Mollong *et al.,* 2025).

Role of Nutrition in Host Immunity and Resistance in cattle

Nutrition profoundly influences host immunity and disease resistance in cattle by providing the necessary nutrients for immune cell energy, proliferation and function, as well as modulating inflammatory responses. Macronutrients like carbohydrates supply energy critical for immune activation, particularly during stresses such as infection or lactation. Proteins and specific amino acids are essential for synthesizing immune molecules including antibodies and cytokines. Deficiencies in energy or protein can impair immune cell activity, reduce phagocytosisand depress natural killer cell function (Spears, 2000). Micronutrients are equally vital vitamins A, D, E and minerals such as zinc, selenium, and copper directly impact immune signalling pathways and antioxidant defence mechanisms. For example, vitamin D influences both innate and adaptive immunity in cattle by regulating antimicrobial peptide production and modulating inflammatory cytokines via intracrine and paracrine signalling pathways in macrophages. Zinc affects the function of many enzymes involved in immunity, while selenium and vitamin E act as antioxidants protecting immune cells from damage by reactive oxygen species produced during the immune response (Nelson er al., 2012). The calcium is essential for milk production and phosphorus for energy transfer and bone development. Calcium levels tend to be higher in lactating/non-pregnant cows and lower after calving. Phosphorus levels are higher in pregnant cows due to increased metabolic demands. The study also notes that the cows were fed green fodder, dry fodder, supplements, concentrates and artificial mineral mixtures, with green fodder being a significant phosphorus source. Adequate mineral nutrition is critical to support metabolic processes, physiological functionsand productivity in cattle. The mineral balance in cattle health, reproductive performance and lactation efficiency (Yaswanthkumar *et al.,* 2021). The periparturient period, a biologically stressful phase in dairy cattle, showcases how nutrient deficits can suppress immune function, increasing susceptibility to infections like mastitis. Overor undernourished animals show impaired immunity and higher disease risks. Conversely, targeted nutritional strategies, such as supplementation with antioxidants, essential fatty acids and trace minerals that can enhance immune competence, reduce inflammation and improve disease resistance. Minerals such as chromium have been shown to improve immune responses during stress (Mordak & Nicpon, 2015; Vlasova *et al.,* 2021).

Nutraceuticals and Bioactive Forages

Condensed tannin-rich forages are known for their strong anthelmintic effects, primarily studied in small ruminants. These forages have been shown to significantly reduce faecal egg counts and worm burdens, with reductions reported up to 76 - 100% in goats. While these condensed tannin-rich plants primarily target internal parasites, they also contribute to overall improved immune health and resilience in animals, potentially benefiting ectoparasite management indirectly. The bioactive compounds in these forages act either directly by interfering with parasite survival or indirectly by enhancing host immunity. Such bioactive plants, often considered nutraceuticals, are gaining attention as natural alternatives or supplements to chemical antiparasitic treatments, promoting sustainable parasite control and improved animal health through diet (Espinoza *et al.,* 2018). Indian studies highlight that condensed tannin-rich forages and tropical tree leave such as *Ficus infectoria, Leucaena leucocephala, Quercus incana, Ziziphus nummularia, Mangifera indica,* and *Psidium guajava* are valuable sources of bioactive compounds for livestock. Supplementing cattle and small ruminant's diets with these forages at moderate levels (1-2% of dry matter intake) has been shown to directly decrease gastrointestinal parasite loads by inhibiting parasite egg hatchability, reducing larval developmentand increasing adult worm mortality. This supplementation also improves nutrient utilization, antioxidant status and both cell-mediated and humoral immune responses making condensed tannin-rich Indian forages a natural and sustainable approach for parasite management. These effects arise both from the direct action of tannins on parasite metabolism and from enhanced protein utilization and immune activation in the host. Strategic use of these locally available tree leaves in Indian livestock diets offers a threefold advantage by supporting parasite control, animal performance, and food safety without residual chemical effects (Uniyal *et al.,* 2017). While these forages may not directly affect ectoparasites, potential indirect benefits include enhanced overall immune health and resilience.

Integrating Nutritional Elements in an Ectoparasite IPM Framework

Integrating nutritional elements into an Integrated Parasitic Management framework in India involves leveraging the dual benefits of traditional medicinal plants and nutraceuticals that provide both antiparasitic effects and nutritional support (Deepak and Sadashiv, 2020).Traditional Indian medicinal plants like Neem (*Azadirachta indica*), *Tinospora cordifolia* (Gulvel), *Vitex negundo* (Nirgudi), and *Acorus calamus* (Vekhand), used in herbal formulations, show significant efficacy in reducing ectoparasitic infestations such as ticks and lice in cattle by 60-63%. These plants not only act as natural parasiticides but also contain bioactive compounds that can stimulate immunity and improve overall animal health. Nutritional benefits include improved antioxidant status and enhanced immune responses, which increase cattle resilience against ectoparasitic stresses (Olubukola *et al.,* 2016). Additionally, nutritional supplementation with vitamins (such as vitamin E), trace minerals (such as selenium and chromium) and essential fatty acids support immune function and stress reduction during ectoparasitic outbreaks. Such nutrients help mitigate the physiological impacts of parasitic stress by reducing oxidative damage and enhancing immune cell function. The IPM framework in Indian livestock production thus combines ethnoveterinary herbal treatments, optimized nutrition, good husbandry practices, pasture management and limited use of chemical treatments to sustainably manage ectoparasites. This holistic approach reduces reliance on synthetic acaricides, lowers resistance development risks and promotes animal welfare and productivity in rural farming systems.

Environmental and Dietary Supplementation Strategies

An integrated approach to parasite control in cattle must address both external parasites (ectoparasites) such as ticks (*Rhipicephalus microplus*), horn flies (*Haematobiairritans*), lice, and mites, and internal parasites (endoparasites) such as gastrointestinal nematodes (*Haemonchus, Ostertagia, Cooperia*), liver flukes (*Fasciola hepatica*), and coccidia (E*imeria sp.*). Both parasite groups compromise animal health and productivity by causing anaemia, weight loss, reduced milk yield and increased susceptibility to other diseases (Sykes & Greer, 2003). While chemical treatments (acaricides, anthelmintics) are important tools, overreliance has led to drug resistance, residues and environmental concerns (Kaplan & Vidyashankar, 2012). Environmental management and targeted nutritional supplementation can strengthen cattle's natural defences against both parasite types, forming the backbone of a sustainable control program.

Environmental Strategies

Control of Ectoparasites by environmental strategies

Pasture Rotation and Spelling: Moving cattle between paddocks allows larval stages of ticks and flies to die off in the absence of a host (Jonsson, 1997).

Manure Management: Frequent removal or spreading of manure in barns and feedlots reduces breeding grounds for flies and mites (Grisi *et al.,* 2014).

Housing Hygiene: Clean, dry, well-ventilated housing prevents build-up of lice and mite infestations (wall *et al.,* 2011).

Biological Control: Introduction of parasitic wasps (*Muscidifurax spp*.), entomopathogenic fungi (*Metarhizium anisopliae*), or predatory beetles can reduce fly populations without chemicals (Cook, 2020).

Control of Endoparasites by environmental strategies

Grazing Management: Rotational grazing and alternate species grazing (e.g., sheep–cattle rotation) lower gastrointestinal worm burdens by disrupting life cycles (Waller, 2006).

Pasture Resting: Allowing pastures to remain ungrazed for several months reduces infective larval contamination (Niezen*et al.,* 1996).

Drainage and Water Control: Improving drainage and fencing off swampy areas helps reduce snail populations that transmit liver fluke (*F. hepatica*) (Howell and Williams, 2020).

Dung Beetle Conservation: Dung beetles help break down manure, reducing larval development of internal and external parasites (Nichols *et al.,* 2008).

Dietary Supplementation Strategies

Minerals:

Copper: Impacts tick reproduction and survival (Ortiz *et al.,* 2014) and also affects nematode metabolism (Waller *et al.,* 2004).

Zinc: Supports skin integrity (barrier against ectoparasites) and immune responses against gut worms (Prasad, 2008).

Selenium: Boosts antioxidant defence, helping control inflammatory damage from parasite infections (McDowell, 2003).

Cobalt: Enables vitamin B_{12} synthesis, critical for energy metabolism during parasite-induced stress (McDowell, 2003).

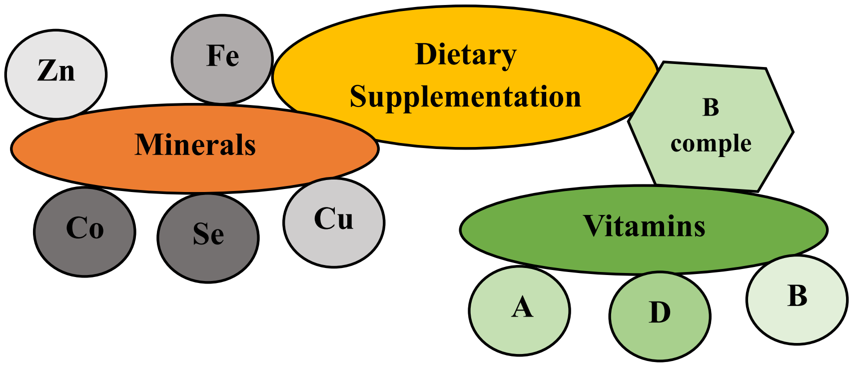
Vitamins:

Vitamin A: Maintains mucosal integrity in both skin and gut, reducing attachment and penetration by ticks and intestinal worms (Stephensen, 2001).

Vitamin E: Protects immune cells from oxidative stress caused by parasite infection (Chandra *et al.,* 1994).

Vitamin D: Regulates immune responses, including macrophage activity against parasites (Aranow, 2011).

Chart 5. Dietary Supplementation Strategies



Botanical & Functional Feed Additives:

Condensed Tannins (e.g., from Lespedeza cuneata, sainfoin): Reduce gastrointestinal worm fecundity and survival while improving protein utilization (Hoste *et al.,* 2015).

Garlic & Neem: Garlic metabolites excreted through the skin can have repellent effects (Huzaifa *et al.,* 2014).

Papaya Seeds & Pumpkin Seeds: Contain bioactive compounds with anthelmintic properties against gastrointestinal nematodes (Dhoot *et al.,* 2024; Grzybek *et al.,* 2016).

Protein and Energy Optimization:

Adequate protein supports antibody synthesis and repair of tissue damage caused by both ecto and endoparasites. The energy fuels the immune cell to get active (Sykes & Greer, 2003). Combining environmental hygiene and pasture management with targeted nutritional supplementation creates a dual defence and lowering the parasite challenge in the environment while boosting the host's capacity to resist and recover from infections. This synergy reduces dependence on synthetic drugs, slows the development of resistanceand enhances long-term herd health and productivity (Kaplan & Vidyashankar, 2012).

Conclusion:

An integrated nutritional approach to ectoparasite management in cattle focuses on improving animal immunity and resilience through balanced feeding, herbal support and good husbandry. Supplying adequate proteins, energy, vitamins and trace minerals strengthens natural defences, while nutraceuticals such as tannin-rich forages, saponin legumes and herbs like neem, garlic and turmeric enhance resistance to parasites. Alongside nutrition, proper sanitation, drainage, housing, stress reduction and rotational grazing reduce parasite breeding and exposure. By combining these measures within an integrated pest management framework, the need for chemical treatments is minimized, helping prevent drug resistance, avoid residues in animal products and protect the environment, while ensuring healthier, more productive and sustainable cattle herds.

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TECHNOLOGICAL FRONTIERS IN ANIMAL HUSBANDRY: ENHANCING PRODUCTIVITY, HEALTH AND ENVIRONMENTAL SUSTAINABILITY

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Abstract:

Recent advancements in animal husbandry have greatly enhanced livestock management, productivity and welfare while addressing sustainability challenges. Precision livestock farming integrates sensors, robotics and smart housing to optimize monitoring and efficiency. Genomic selection and modern breeding accelerate genetic improvement, while nutrigenomics supports targeted dietary strategies for better performance. Automation and artificial intelligence, particularly in dairy production, promote evidence-based decision making. Novel vaccines and diagnostic tools advance disease prevention, while sustainable production systems based on circular economy principles enhance resource efficiency and environmental stewardship. Climate resilience is strengthened through genetic innovations and adaptive management. Integrated waste-to-energy solutions and welfare-enhancing practices further position animal husbandry as a driver of sustainable food security and responsible livestock care. Ethical and welfare considerations are increasingly prioritized through enriched housing, humane handling and comprehensive certification schemes. These multifaceted innovations in animal husbandry are transforming the sector into a driver of sustainable food security, environmental stewardship and responsible animal care, aligning with global sustainability goals and societal expectations.

Keywords: Precision Livestock Farming, Sustainable Production Systems, Artificial Intelligence, Animal Welfare.

1. Introduction:

Animal husbandry is a vital branch of agriculture that focuses on the management, breeding, and care of animals raised for diverse purposes such as meat, milk, fiber, and other products. Originating with the domestication of animals during the Neolithic Revolution, it has been an intrinsic part of human civilization, shaping societies through contributions to food security and livelihood. Over the centuries, systematic breeding and improved management practices, notably during developments like the British Agricultural Revolution, have dramatically increased productivity and adapted animal farming for different ecological contexts

(Kistanova *et al.,* 2024). In recent years, the field has been transformed by scientific and technological advances that intersect biology, genetics, nutrition, and engineering. These innovations have enabled more efficient, productive and sustainable livestock systems by leveraging genetics, nutritional science, reproductive technologies, and disease management strategies. For instance, modern tools like artificial insemination, in vitro fertilization and genomic selection are now commonly integrated to enhance animal performance, health, and adaptability to environmental challenges (Kazemi, 2025).

A particularly transformative development is the rise of precision livestock farming (PLF), which applies electronic sensors, automation, and data analytics to monitor and optimize the health, productivity, and welfare of animals. PLF enables real-time tracking of factors such as nutrition, growth, reproductive status and environmental conditions, supporting timely interventions and improved resource management. This data-driven approach addresses the mounting global demand for animal products while also increasing accountability regarding environmental impacts, animal welfare and sustainability (Trapanese *et al.,* 2025). Animal husbandry today stands at the crossroads of tradition and innovation. It not only seeks to boost productivity and ensure economic viability for farmers but also to meet global standards for animal welfare, resource efficiency, and environmental stewardship. As the sector continues to adapt to challenges such as changing consumer preferences, climate change, and land scarcity, integrating emerging technologies and management practices is crucial for a resilient and sustainable future (Hendriks *et al.,* 2025).

2. Precision Livestock Farming: Sensors, Robotics and Smart Housing

Precision Livestock Farming is a modern agricultural practice that uses technology to monitor and manage farm animals more effectively. It involves the use of sensors and digital tools to collect data on animal health, behavior, and environment. This approach helps farmers detect issues early, improve animal welfare and optimize production. By relying on real-time data and automation, precision livestock farming offers greater efficiency and sustainability in livestock management.

2.1 Sensors in Precision Livestock Farming

Sensors play a pivotal role in Precision Livestock Farming by enabling real-time monitoring of animal health, welfare, and productivity. Modern sensors can track physiological parameters such as heart rate, respiration, body temperature, and activity levels, providing early warning signs of diseases like mastitis or lameness. Additionally, sensors embedded in feeding systems monitor feed intake and water consumption, ensuring nutritional balance and detecting anomalies that may indicate health issues. Environmental sensors further monitor barn conditions, including temperature, humidity, and ammonia levels, which are crucial for maintaining animal comfort and reducing stress (Ozger *et al.,* 2024). Advancements in sensor technology have led to the development of wearable devices like smart collars, ear tags and leg bands that use GPS and accelerometers to track animal movement and grazing patterns (Distante *et al.,* 2025).

2.2 Robotics in Livestock Farming

Robotics has revolutionised repetitive and labour-intensive tasks in animal husbandry, significantly enhancing operational efficiency. One of the most widely adopted robotic applications is automated milking systems, which allow cows to voluntarily enter milking stations, reducing human intervention and stress on animals. These systems not only automate milking but also collect real-time data on milk yield, quality, and somatic cell counts, enabling early disease detection and herd management optimization (VanderZaag *et al.,* 2025). Other robotic applications include feeding robots that deliver precise rations based on individual animal requirements, ensuring optimal nutrition while minimizing feed wastage. Additionally, drones are increasingly used in open grazing systems for monitoring livestock location and detecting abnormalities such as injuries or predator threats. By reducing manual labor and improving precision, robotics contributes to sustainable farming practices, enhanced productivity, and better animal welfare standards (Jiang *et al.,* 2025).

2.3 Smart Housing Systems

Smart housing integrates automation, Internet of Things (IoT), and data analytics to create an environment conducive to animal health and productivity. These systems use advanced climate control technologies that regulate temperature, humidity, and ventilation based on real-time sensor data, ensuring optimal comfort for livestock. Proper environmental control reduces heat stress and respiratory problems, which are common issues in intensive farming systems (Dawkins, 2025). Smart housing also includes automated lighting systems, waste management solutions, and robotic bedding systems that improve hygiene and animal comfort. Integration with digital platforms enables farmers to remotely monitor and control housing conditions through mobile applications or cloud-based systems. The combination of data analytics and machine learning allows predictive maintenance of housing equipment and anticipatory adjustments in environmental conditions, thus enhancing resource efficiency (Marchegiani *et al.,* 2025).

3. Genomic Selection and Breeding for Livestock Improvement

Genomic selection and breeding for livestock improvement is a scientific approach that uses information from an animal's entire genetic makeup to guide breeding decisions. By analyzing DNA markers across the animal genome, this method allows the prediction of desirable traits such as growth rate, milk production, or disease resistance at an early age. It enables the selection of animals with the best genetic potential, leading to faster genetic progress and more efficient livestock improvement. This approach has transformed traditional breeding by increasing accuracy and reducing the time needed to develop superior animals.

3.1 Principles of Genomic Selection

Genomic selection (GS) is an advanced breeding approach that uses genome-wide molecular markers to predict the genetic merit of animals at an early age. Unlike traditional selection methods that rely on phenotypic performance and pedigree information, Genomic selection incorporates thousands of single-nucleotide polymorphism distributed across the genome. These markers are statistically associated with traits of interest, enabling the estimation of genomic breeding values. This method significantly improves accuracy in predicting an animals future performance for economically important traits such as milk yield, growth rate, feed efficiency, and disease resistance (Tade and Melesse, 2024). The primary advantage of Genomic selection is its ability to shorten the generation interval by allowing breeders to select animals before they reach maturity. For instance, young bulls can be evaluated for breeding potential without waiting for progeny testing results. This accelerates genetic gain and enhances the efficiency of selection programs. Moreover, GS is particularly valuable for traits that are difficult or expensive to measure, such as fertility, longevity, and disease resistance, thereby making livestock improvement programs more comprehensive and cost-effective (Xu *et al.,* 2020).

3.2 Genomic Tools and Technologies in Livestock Breeding

The success of genomic selection depends on advanced tools and technologies for genotyping and bioinformatics analysis. High-throughput genotyping platforms, such as single-nucleotide polymorphism chips and next-generation sequencing, allow for rapid and cost-effective screening of large populations for thousands of genetic markers. These technologies are integrated with sophisticated statistical models like genomic Best Linear Unbiased Prediction and Bayesian methods, which combine marker effects to predict genomic breeding values with high accuracy (Escamila *et al.,* 2025). In addition to genotyping, genome-wide association studies play a crucial role in identifying quantitative trait loci linked to production, health, and reproductive traits. Bioinformatics and big data analytics further enhance genomic selection programs by managing large datasets, detecting complex genetic interactions, and integrating multi-omics information such as transcriptomics and epigenomics. These technological advancements make it possible to implement precision breeding strategies that maximize genetic progress while maintaining genetic diversity within livestock populations (Sun *et al.,* 2025).

3.3 Applications and Benefits in Livestock Improvement

Genomic selection has been successfully implemented in dairy cattle breeding programs worldwide, resulting in significant improvements in milk production, udder health, and fertility. Similarly, in beef cattle, genomic selection accelerates genetic gains in growth performance, feed conversion efficiency and carcass quality. In small ruminants like sheep and goats, genomic selection contributes to enhancing wool quality, disease resistance and reproductive traits. Poultry and swine industries also leverage genomic selection to improve traits such as growth rate, egg production, meat quality and robustness against diseases. The benefits of genomic selection extend beyond productivity. It enables selection for traits associated with animal welfare, sustainability and adaptability to climate change.

4. Nutrigenomics and Advanced Feed Formulations for Animal Health

Nutrigenomics is a scientific field that studies how nutrients in animal feed interact with genes to influence gene expression and regulation. This discipline seeks to understand the relationship between diet and the genetic makeup of animals to improve their health, growth, and productivity. By tailoring feed formulations to the specific genetic profiles of animals, nutrigenomics aims to enhance immune response, prevent diseases and optimize overall animal performance. Advanced feed formulations based on nutrigenomics provide targeted nutrition that supports better animal health and more efficient livestock production.

4.1 Nutrigenomics in Animal Health

Nutrigenomics is the study of how nutrients and dietary components influence gene expression and metabolic pathways in animals. This emerging field combines nutrition, genomics, and molecular biology to understand how specific nutrients interact with an animal's genome to affect physiological processes, health, and productivity. By identifying these nutrient–gene interactions, nutrigenomics enables precision feeding strategies tailored to an animals genetic makeup, leading to optimized health and performance (Deb and Payan-Carreira, 2022).

4.2 Advanced Feed Formulations for Animal Health

Advanced feed formulations go beyond conventional energy and protein supplementation to include functional ingredients that support gut health, immunity and overall well-being. These formulations often incorporate probiotics, prebiotics, enzymes, organic minerals, essential oils and phytobiotics, which work synergistically to enhance nutrient absorption, maintain intestinal integrity, and reduce pathogenic load in the gut. Precision nutrition technologies, combined with nutrigenomic insights, allow for the development of customized feeds based on species, production stage and health status. In addition, the inclusion of bioactive compounds and nano-additives in feed formulations has gained attention for improving feed efficiency and reducing environmental impact (Usigbe *et al.,* 2025).

5. Role of Probiotics and Prebiotics in Animal Nutrition

Probiotics and prebiotics play an important role in animal nutrition by supporting the balance and health of the gastrointestinal system. Probiotics are beneficial live microorganisms that help improve digestion, enhance immune function, and protect animals from harmful pathogens. Prebiotics are non-digestible food ingredients that promote the growth of these beneficial microbes in the gut. Together, they help maintain a healthy intestinal environment which improves nutrient absorption, increases disease resistance, and supports overall animal growth and productivity. The use of probiotics and prebiotics reduces the need for antibiotic growth stimulants and contributes to safer and more sustainable livestock production (Ravanal *et al.,* 2025).

5.1 Probiotics in Animal Nutrition

Probiotics are live microorganisms that, when administered in adequate amounts, confer health benefits to the host by improving gut microbiota balance. In animal nutrition, probiotics play a crucial role in enhancing gut health, nutrient absorption, and overall immunity. Common probiotic strains include species of Lactobacillus, Bifidobacterium, Bacillus, and Saccharomyces cerevisiae. These beneficial microbes compete with pathogenic bacteria in the gastrointestinal tract, reducing incidences of infections such as salmonellosis and colibacillosis. Probiotics also produce antimicrobial substances such as bacteriocins and organic acids, which inhibit harmful microbes and maintain a healthy gut environment. Beyond gut health, probiotics improve feed efficiency and growth performance by stimulating digestive enzyme activity and improving nutrient bioavailability. In ruminants, probiotics enhance fiber digestion and stabilize rumen pH, reducing the risk of acidosis and improving milk yield and composition (Idowu *et al.,* 2025).

5.2 Prebiotics in Animal Nutrition

Prebiotics are non-digestible feed components, such as oligosaccharides, that selectively stimulate the growth and activity of beneficial gut microbes. Unlike probiotics, prebiotics are not live organisms but act as substrates for desirable gut bacteria, promoting a balanced microbiome. By enhancing populations of Lactobacillus and Bifidobacterium, prebiotics help improve gut integrity, inhibit pathogenic bacteria, and reduce the incidence of gastrointestinal disorders. This effect contributes to better nutrient utilization, improved feed conversion ratios, and overall animal performance. Prebiotics also have an immunomodulatory role by enhancing the production of short-chain fatty acids such as butyrate, which serves as an energy source for intestinal cells and strengthens the gut barrier. They are increasingly being combined with probiotics to achieve synergistic benefits in animal nutrition. The application of prebiotics is particularly valuable in weaning animals, such as piglets and calves, where gut microbiota disruption is common. Through these mechanisms, prebiotics contribute to improved animal health, reduced mortality, and sustainable livestock production without over-reliance on antibiotics (Swanson *et al.,* 2025).

6. Automation and Artificial Intelligence in Dairy Management

Automation and artificial intelligence are transforming dairy management by improving efficiency, productivity, and animal welfare. These technologies use sensors, machine learning, and robotics to monitor and manage various aspects of a dairy farm such as individual cow health, milk production, feeding schedules, and breeding cycles. Automation reduces manual labor by enabling robotic milking and feeding systems that adapt to each animal's needs. Artificial intelligence analyzes vast amounts of data in real time to detect early signs of illness, optimize nutrition, predict milk yields, and support decision-making. Together, automation and AI help farmers run more sustainable, precise, and profitable dairy operations while enhancing the well-being of the animals.

6.1 Automation in Dairy Management

Automation in dairy farming has transformed traditional practices by introducing systems that reduce manual labor, improve efficiency, and ensure consistent animal care. One of the most significant advancements is automated milking systems (AMS), which allow cows to voluntarily enter milking stations where robotic arms handle teat cleaning, attachment, and milking without human intervention. These systems not only reduce labor costs but also enhance animal welfare by offering flexible milking schedules that align with the cows' natural behavior. Alongside AMS, automatic feeders deliver precise rations based on individual cow requirements, improving feed efficiency and reducing wastage. Other automated systems include barn cleaning robots, ventilation control systems, and heat detection monitors. Automated scrapers maintain hygiene by removing manure, reducing the risk of hoof diseases and infections. Climate control systems regulate temperature and humidity, ensuring cow comfort during heat stress conditions. Additionally, automated calf feeders and water dispensers support early-life nutrition, which is critical for future productivity. Overall, automation enhances productivity, animal welfare and resource utilization, making it an essential component of modern dairy farming (Bhoj *et al.,* 2024).

6.2 Artificial Intelligence (AI) in Dairy Management

Artificial Intelligence has brought data-driven decision-making to dairy management, improving herd health monitoring, productivity prediction, and operational efficiency. AI algorithms process vast amounts of data collected from sensors, milking robots, wearable devices, and cameras to provide actionable insights. Moreover, AI enhances precision feeding by analyzing cow-specific data, such as weight, lactation stage and metabolic health, to formulate tailored diets that maximize milk yield while minimizing feed costs. Machine learning models are also used for predictive analytics, such as forecasting milk production trends, identifying at-risk animals and optimizing farm resources. Computer vision integrated with AI is increasingly used for real-time monitoring of cow behavior, lameness detection, and stress assessment. By combining automation with AI, dairy farms achieve higher profitability, sustainability and improved animal welfare standards (Khanashyam *et al.,* 2025).

7. Advances in animal health: Vaccines, diagnostics, and disease control

Advances in animal health have become crucial components in modern animal husbandry, underpinning efforts to improve livestock productivity, welfare, and disease control while ensuring sustainability and food security. Vaccines and diagnostics represent the forefront of innovation, transforming the way diseases are prevented, detected, and managed in livestock populations. The advent of novel vaccine technologies such as mRNA and heat-resistant formulations has significantly enhanced the efficiency and scalability of immunization programs, overcoming limitations like cold chain dependency and enabling broader protection across diverse species and regions (Ducrot *et al.,* 2024). Concurrently, breakthroughs in diagnostic tools including molecular diagnostics, microfluidics, and artificial intelligence-based sample analysis are facilitating early, precise detection of diseases at the point-of-care, thereby reducing antibiotic use and mitigating zoonotic disease transmission risks. These innovations not only promote animal welfare and productivity but also play pivotal roles in safeguarding public health and advancing the "One Health" agenda that links animal, human, and environmental health (Roy *et al.,* 2025).

7.1 Innovative vaccine technologies reshaping disease prevention

The landscape of veterinary vaccines is being reshaped by a wave of technological breakthroughs that optimize both efficacy and delivery. mRNA vaccines exemplify a revolutionary approach by instructing the animal's own cells to produce antigenic proteins, thereby eliciting a robust immune response without the risks associated with live or inactivated pathogens. This technology enables faster vaccine development cycles and production scalability, making it particularly suitable for emerging infectious diseases (Bhattacharjee and Sharma, 2025). Heat-stable vaccines represent another key advancement; their ability to retain potency without refrigeration has profound implications for improving vaccination coverage in tropical and resource-limited settings. Precision delivery systems, including *invivo* vaccination for poultry and automated oral vaccines for aquaculture, further enhance immunization efficiency. Additionally, autogenous vaccines tailored to specific herd pathogen strains provide highly targeted protection, reducing disease outbreaks and fostering herd immunity. These vaccine innovations are integral to reducing disease burden, lowering economic losses, and supporting sustainable livestock production worldwide (Abd El-Ghany, 2024).

7.2 Cutting-edge diagnostics and disease control strategies

Advancements in animal disease diagnostics and control strategies are rapidly evolving, driven by improvements in technology and data analytics. Molecular diagnostics offer highly sensitive and specific methods for detecting pathogens and resistance markers at early stages, allowing for timely intervention. Microfluidic devices enable on-site testing with minimal sample volumes, accelerating decision-making and enhancing field applicability. Artificial intelligence and machine learning are revolutionizing diagnostics by automating sample analysis, offering rapid detection of parasites, and providing predictive disease models that guide proactive health management (Das *et al.,* 2024). These tools collectively support the reduction of antimicrobial use by enabling targeted treatments, thus addressing antibiotic resistance challenges. Complementing diagnostics, integrated disease control strategies emphasize biosecurity measures, vaccination programs, and digital health monitoring to prevent disease spread and restrict zoonotic transmissions (Sharan *et al.,* 2023).

8. Sustainable animal production systems and circular economy

Sustainable animal production systems guided by the principles of the circular economy represent a dynamic evolution in animal husbandry, addressing the urgent need to balance productivity with environmental stewardship. Traditional linear livestock production, characterized by high resource consumption and waste generation, has shown limitations in sustainability and environmental impact, prompting a search for new models (Duncan *et al.,* 2023). The circular economy framework seeks to mimic natural ecosystems by promoting resource efficiency, waste minimization, and the reuse and recycling of by-products within animal production systems. These approaches emphasize closed-loop systems where waste streams such as manure, crop residues, and processing by-products are valorised as inputs, reducing environmental pollution and enhancing farm profitability (Ramirez *et al.,* 2021).

8.1 Transitioning from linear to circular models in animal husbandry

The shift towards circular animal production involves fundamental changes in how resources are managed at the farm and territorial levels. Unlike conventional intensive livestock systems that rely heavily on external feed inputs and generate significant wastes, circular systems focus on maximizing the utility of local resources while minimizing environmental footprints. Innovative closed-loop strategies include the transformation of manure into biogas and organic fertilizers, the use of agro-industrial by-products as feed supplements, and integrated crop-livestock systems that enhance nutrient cycling and biodiversity (Shamsuddoha and Nasir, 2024). Such practices not only reduce dependence on synthetic inputs but also create economic value from agricultural waste. The social and economic dimensions of this transition are also critical; consumer demand for sustainably produced animal products and supportive policy frameworks catalyse adoption. Furthermore, precision livestock farming technologies enable efficient monitoring and management of animal health, welfare, and environmental emissions, facilitating the practical implementation of circular practices (Himu and Raihan, 2024).

8.2 Technological and systemic innovations supporting circularity

Advances in smart farming technologies and systemic approaches underpin the drive towards sustainable circular animal production systems. Precision livestock farming, utilizing sensors, IoT, and data analytics, optimizes feed efficiency, minimizes waste, and monitors environmental impacts, thereby reducing input use and emissions. Nutrient recovery technologies convert waste streams into valuable bio-based products such as organic fertilizers and renewable energy, closing resource loops within agricultural landscapes (Papakonstantinou *et al.,* 2024). Collaborative models foster sharing of resources, knowledge, and infrastructure among farmers, feeding into broader circular supply chains that enhance sustainability and economic resilience. Together, these technological and systemic innovations provide the means to reconcile high productivity with ecological balance, enabling animal husbandry to contribute meaningfully to climate change mitigation, resource conservation, and rural development (Heydari, 2024).

9. Climate resilience in livestock production

Climate resilience in livestock production is rapidly becoming a cornerstone of sustainable animal husbandry amid the escalating challenges posed by global climate change. The livestock sector is particularly vulnerable to climate-induced stresses such as rising temperatures, erratic rainfall, droughts, and emerging diseases, all of which threaten animal health, productivity, and the livelihoods of farmers worldwide (Awazi, 2025). Advancements in animal husbandry now emphasize integrating climate adaptation strategies that improve the ability of livestock systems to withstand, recover from, and adapt to these environmental pressures. By harnessing genetic improvement, precision livestock farming technologies, and diversified farming systems, the sector aims to enhance resilience while ensuring food security and sustainable development under shifting climatic scenarios. These innovations also align with broader efforts to reduce the environmental footprint of livestock production and contribute to climate change mitigation (Saba *et al.,* 2024).

9.1 Genetic and management innovations for climate-resilient livestock

A major advancement towards climate resilience in animal husbandry involves the genetic improvement and diversification of livestock species and breeds. Indigenous and locally adapted breeds, often possessing inherent tolerance to heat, drought, and diseases, are increasingly valued for breeding programs aimed at developing climate-resilient herds. For instance, thermotolerant breeds like Zebu cattle and certain goat and sheep varieties showcase physiological and behavioural traits that enable survival and productivity in harsh, arid environments (Engdawork *et al.,* 2024). Alongside genetics, improved management practices such as enhanced feeding regimes, rotational grazing, and provision of shade and water sources help mitigate heat stress and maintain animal welfare. Capacity-building initiatives that educate farmers on adaptive techniques and encourage mixed crop-livestock systems also contribute substantially to building resilient livestock systems. These combined approaches optimize productivity, reduce livestock mortality from climatic shocks, and support ecosystem health through better nutrient cycling and biodiversity conservation (Atapattu *et al.,* 2025).

9.2 Precision livestock farming and data-driven climate adaptation

The integration of precision livestock farming and data-enabled innovations has opened new frontiers in climate resilience by enabling real-time monitoring and management of animal health and environmental conditions. IoT sensors, wearable devices, and remote sensing technologies track vital parameters such as temperature, humidity, feed intake, physiological stress indicators, and disease symptoms, providing early detection of heat stress and other climate-related health risks (Bashiru and Oseni, 2025). Advanced data analytics and artificial intelligence facilitate predictive modelling and decision support, allowing farmers to implement timely interventions tailored to specific microclimates and animal groups. Such technology-driven solutions increase resource-use efficiency, reduce greenhouse gas emissions, and improve the overall sustainability of livestock production. Furthermore, PLF contributes to enhanced animal welfare and productivity by minimizing losses and optimizing reproductive performance even under challenging climatic conditions (Neethirajan, 2024).

10. Waste management in animal husbandry: Biogas and biofertilizer production

Waste management in animal husbandry is a critical component of sustainable livestock production, combining environmental responsibility with the potential to generate renewable energy and nutrient-rich fertilizers. Traditional waste disposal methods often result in environmental pollution through the release of greenhouse gases like methane and nitrous oxide as well as water contamination. However, recent advances in anaerobic digestion and bioconversion technologies have transformed animal waste from an environmental liability into valuable resources such as biogas and biofertilizers (Sadeghpour and Afshar, 2024). Biogas production from animal manure not only helps mitigate climate change by capturing methane emissions but also provides a clean and renewable source of energy that can be utilized for cooking, heating, and electricity generation on farms, thereby reducing dependence on fossil fuels. The digest from biogas plants serves as an organic biofertilizer rich in nutrients, enhancing soil fertility, reducing chemical fertilizer use, and promoting circular economy principles within animal farming systems. These integrated waste management practices represent a significant stride forward in animal husbandry by coupling environmental conservation with economic benefits and energy security (Myalkovsky and Pantsyreva, 2023).

10.1 Biogas production: Unlocking renewable energy from livestock waste

The production of biogas through anaerobic digestion of livestock manure has gained widespread adoption as a sustainable waste management solution in modern animal husbandry. Anaerobic digesters facilitate the breakdown of organic matter by microorganisms in the absence of oxygen, releasing biogas predominantly composed of methane and carbon dioxide. Advances in digester design, including temperature control, mixing technologies and feedstock optimization, have increased gas yields and operational efficiency (Alengebawy *et al.,* 2024).

Mesophilic and thermophilic digestion processes are tailored based on feedstock characteristics and local conditions to maximize energy recovery. Beyond energy production, biogas plants help reduce environmental pollution by minimizing odours and pathogens, lowering the risk of groundwater contamination and mitigating greenhouse gas emissions. Policy initiatives and financial incentives further drive the adoption of biogas technologies in livestock farming, enhancing rural livelihoods and supporting decentralized renewable energy generation (Yanga *et al.,* 2025).

10.2 Biofertilizer production and its role in sustainable agriculture

The effluent or digestate resulting from biogas production offers an excellent source of biofertilizer, rich in organic matter and essential nutrients such as nitrogen, phosphorus and potassium. This biofertilizer not only replenishes soil fertility but also improves soil structure and moisture retention, fostering healthier crop growth and increased agricultural productivity. Unlike synthetic fertilizers, biofertilizers derived from animal waste are environmentally benign, reducing the risks of soil acidification, nutrient runoff and groundwater contamination (Chojnacka *et al.,* 2024). Advances in biofertilizer formulation and application techniques have enhanced their stability, nutrient availability, and compatibility with various cropping systems. Furthermore, integrating biofertilizer use with precision agriculture technologies optimizes input application, thus promoting more sustainable and efficient farming systems (Fadiji *et al.,* 2024).

11. Ethical and welfare practices in modern animal husbandry

Ethical and welfare practices in modern animal husbandry have gained significant attention as integral components of sustainable livestock management, driven by societal concerns about animal well-being and the recognition that improved welfare correlates strongly with enhanced productivity and product quality. Modern animal husbandry no longer solely focuses on maximizing output but increasingly prioritizes the health, comfort, and natural behaviours of animals. This shift reflects growing consumer demand for ethically sourced animal products and the inclusion of welfare standards in certification schemes (Zhang *et al.,* 2024). Advances in housing design, environmental enrichment, humane handling, and stress reduction techniques contribute to better physiological and psychological states in animals, which in turn reduce disease incidence and improve reproductive efficiency.

11.1 Innovations in housing and environmental enrichment for improved welfare

Housing systems designed for modern animal husbandry emphasize optimal environmental control to safeguard animal health and welfare. Innovations such as enhanced ventilation, temperature regulation, and lighting improve comfort and reduce heat and cold stress, factors critically linked with animal well-being and productivity. Environmental enrichment, including provision of manipulable materials, social interaction opportunities, and naturalistic spaces, mitigates boredom and stress-related behaviours, thereby fostering normal behavioural expressions. Such enriched environments have been shown to have positive effects on immune function and growth performance. Advances in sensor technologies integrated into housing systems enable continuous monitoring of individual animal health indicators like movement, feeding behaviour and vocalization, leading to early detection of illness and welfare compromises (Neethirajan *et al.,* 2024).

11.2 Ethical handling, disease management, and welfare certification

Ethical handling practices focus on minimizing pain and fear during everyday management routines such as transport, veterinary interventions and slaughter. The promotion of low-stress handling techniques and training programs for farm workers have become central to welfare improvements. Alongside handling, advances in disease prevention and control, including vaccination, biosecurity measures and rapid diagnostics, play a pivotal role in safeguarding welfare by reducing suffering and productivity loss caused by illness (Anthony, 2025). Increasingly, comprehensive welfare certification schemes and audit systems are implemented to verify adherence to welfare standards, providing transparency and meeting consumer expectations. These certifications incentivize farmers to maintain high welfare benchmarks and strengthen market access. The combination of ethical management, health maintenance and formal welfare assurance constitutes a modern framework for responsible animal husbandry that supports ethical imperatives and economic viability (Jensen *et al.,* 2024).

Conclusion:

Advances in animal husbandry are reshaping livestock management through precision farming, genomic selection, nutrigenomics, automation, artificial intelligence, improved animal health, sustainable systems, waste management and ethical care. Precision livestock farming employs sensors, robotics and smart housing to monitor health, behavior and environment, enabling early issue detection and optimized productivity. Genomic selection and nutrigenomics-based feed formulations enhance performance, adaptability and welfare. Automation and AI in dairy management improve efficiency and decision-making. New vaccines, diagnostics and disease control strategies safeguard animal and public health. Sustainable systems guided by circular economy principles reduce waste and environmental impact, while biogas and biofertilizers transform livestock waste into renewable resources. Prioritizing welfare through enriched housing and humane handling, modern husbandry balances productivity, sustainability and animal well-being.

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ADVANCING SUSTAINABLE CROP MANAGEMENT: TECHNOLOGIES AND TRENDS IN MODERN AGRICULTURE

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Abstract:

Precision agriculture (PA) is transforming farming through technologies like IoT, drones, and artificial intelligence, enabling real-time monitoring, automation, and data-driven decisions to enhance productivity and sustainability. IoT sensors support targeted irrigation, nutrient management, and crop surveillance, while drones and AI deliver detailed crop health analysis. Climate-smart agriculture (CSA) emphasizes resilient crop varieties, water-efficient systems, and digital innovations to adapt to climate change. Emerging nanotechnologies, including nano-fertilizers, nano-pesticides, and nano-sensors, improve nutrient delivery, pest control, and monitoring accuracy. CRISPR and genome editing accelerate the development of stress-tolerant, high-yield crops. Biofertilizers and biopesticides provide eco-friendly alternatives that improve soil health and pest management. Vertical farming and controlled environment systems increase resource efficiency and food production in urban areas. Water-smart methods such as drip irrigation, hydroponics, and aquaponics conserve water while sustaining yields. Together, these innovations strengthen food security, conserve natural resources, and support sustainable agricultural development.

Keywords: Crop Management, Smart Agriculture, Climate Resilience, Sustainability, Resource Efficiency

1. Introduction:

Agriculture is at the forefront of a global transformation as it seeks to address pressing challenges such as food security, resource scarcity, population growth, and climate change. Traditional farming methods, though once sufficient, are increasingly inadequate in meeting the rising demand for safe, sustainable, and high-quality food production. In this context, modern innovations such as Precision Agriculture (PA), Climate-Smart Agriculture (CSA), biotechnology, and controlled farming systems are reshaping the agricultural landscape. Precision agriculture leverages advanced technologies including the Internet of Things (IoT), drones, and artificial intelligence (AI) to optimize crop management through real-time monitoring, predictive analytics, and automated interventions (Saleem *et al.,* 2024). These tools enable targeted irrigation, precise nutrient delivery, and early detection of crop stress, thereby enhancing yields while minimizing input waste and environmental impacts. Complementing PA, climate-smart agriculture focuses on building resilience against climatic uncertainties through the adoption of drought-tolerant crop varieties, water-efficient irrigation practices, conservation agriculture, and digital innovations that integrate sustainability into farming systems. Parallel to these developments, nanotechnology offers nano-fertilizers, nano-pesticides, and nanosensors that improve efficiency in nutrient use, pest control, and crop health monitoring (Fathi Qarachal and Alizadeh, 2025). Similarly, CRISPR and genome editing technologies are accelerating the development of high-yield, stress-tolerant, and nutritionally enhanced crops. Eco-friendly inputs such as biofertilizers and biopesticides provide sustainable alternatives to synthetic chemicals, contributing to soil health and biodiversity conservation. Additionally, innovative systems such as vertical farming, hydroponics, aquaponics, and controlled environment agriculture are redefining food production in urban and resource-limited settings (Kapoor *et al.,* 2024). Collectively, these advancements represent a paradigm shift toward sustainable, technology-driven agriculture, offering integrated solutions to ensure global food security, resource conservation, and climate resilience.

2. Precision Agriculture: Role of IoT, Drones, and AI in Crop Management

PA marks a paradigm shift in crop management, leveraging cutting-edge tools such as the IoT, drones, and AI to address challenges of resource efficiency, productivity, and sustainability. Traditional farming techniques, once sufficient, have fallen behind as food demand rises and environmental pressures intensify. PA employs real-time data acquisition, smart automation, and machine learning to apply the right intervention at the right place and time optimizing yields, minimizing input waste, and reducing environmental impact. Recent scientific advances highlight the powerful integration of sensor technology, digital imaging, and AI-based analysis in transforming how crops are monitored and managed, driving agriculture into a new era of data-driven decision-making (Sharma and Shivandu, 2024).

2.1 IoT and Sensor Technologies: The Foundation of Smart Crop Management

The deployment of IoT devices across fields underpins the promise of PA. Modern sensor systems including soil moisture, pH, and plant health sensors deliver high-resolution, real-time data about microenvironmental variations. IoT-enabled monitoring networks facilitate: (1) Targeted Irrigation: Studies confirm that IoT-driven variable rate irrigation and advanced systems like drip irrigation can reduce water use by 30–50% and boost yields by 10 –20%. (2) Nutrient Optimization: Sensors and analytics enable precise fertilizer application, increase nutrient use efficiency by up to 20% and reducing fertilizer costs by 25%. Real-time feedback prevents resource overuse and ensures optimal plant health. (3) Continuous and Predictive Monitoring: Integration with cloud platforms allows for remote access, mobile alerts, and predictive analytics, empowering farmers to anticipate problems such as emerging pest infestations or water stress before yield losses occur. Recent reviews emphasize that connecting sensor networks with IoT and cloud computing enables farm-wide surveillance and adaptive management, though challenges remain in data management, system cost, and rural connectivity (Aarif *et al.,* 2025 and Abdelmoneim *et al.,* 2025).

2.2 Drones and Artificial Intelligence

Aerial and on-ground drones, enabled by AI-powered analytics, have revolutionized information gathering and crop health assessment. Advances include: (1) High-Resolution Imaging & Real-Time Crop Monitoring: Drones equipped with multispectral and thermal cameras map crop vigor, stress, diseases, and yield variability. Early detection enables site-specific, rapid intervention improving yields by up to 25% and reducing input costs by 15%. (2) AI-Driven Decision Support: Machine learning models analyse drone imagery and sensor data to predict disease outbreaks, forecast yields, and automate recommendations for fertilization or pesticide application. AI-powered irrigation and fertilization can increase yields by 5–15% using 25–40% less water and 30–40% less fertilizer, as reported in recent field studies. (3) Automation and Efficiency: Robotics and AI-driven vehicles (including drone-based spraying and robotic harvesters) reduce labour costs by up to 40% and boost operational efficiency by 35%. Automated, data-driven farm platforms are advancing toward fully autonomous, self-optimizing crop systems (Imran and Li, 2025).

3.Climate-Smart Agriculture

CSA emerges as a vital and progressive approach designed to tackle the multifaceted challenges posed by global climate change to agricultural systems worldwide. It is an integrative framework that simultaneously aims to increase agricultural productivity and farmer incomes, enhance resilience and adaptation to climate variability, and significantly reduce greenhouse gas emissions wherever possible. Recognizing the complex interplay between farming practices and the environment, CSA incorporates the latest scientific advancements and technology to foster sustainable agricultural development. As climate uncertainties grow, CSA offers a pathway to secure food systems and protect natural resources through innovative practices and data-driven decision-making, representing a transformative shift in global agriculture (Raihan, 2024).

3.1 Advances in Climate-Resilient Crop and Resource Management

A profound advancement within CSA is seen in the development and widespread adoption of resilient crop and resource management strategies that stand up to climatic stresses. These include the breeding and utilization of drought-tolerant and pest-resistant crop varieties developed through cutting-edge biotechnologies and traditional breeding methods, which ensure greater yield stability despite variable and harsh weather conditions. In conjunction with genetic improvements, water-efficient technologies such as precision drip irrigation, rainwater harvesting, and soil moisture sensors connected via IoT networks facilitate judicious water use, thus enhancing drought resilience while conserving vital water resources (Hussain *et al.,* 2021). Enhancing soil health through conservation agriculture techniques such as minimal tillage, cover cropping, and organic amendments further ensures sustainability by improving fertility and increasing soil carbon sequestration, which also plays a critical role in mitigating climate change. These integrated measures solidify the foundation of climate-smart farms that are more productive, resource-efficient, and able to adapt over time to evolving environmental challenges (Srivastava, 2025).

3.2 Digital Innovations Enabling Precision and Sustainability

Complementing advances in crop and resource management are transformative developments in digital technology and smart monitoring systems. Real-time data acquisition through satellites, drones, and ground sensors has dramatically enhanced the precision of agricultural monitoring by enabling early detection of crop stress, pest infestations, and climate-induced anomalies. The integration of artificial intelligence and machine learning algorithms allows for sophisticated analysis of this diverse data, providing predictive insights that optimize input use, improve pest and disease management, and forecast yields with unprecedented accuracy (Gebresenbet *et al.,* 2023). Furthermore, these technologies support the adoption of regenerative practices, such as agroforestry and biochar application, that not only reinforce ecosystem services but also contribute to carbon sequestration and biodiversity conservation. By empowering farmers with these tools and knowledge, climate-smart agriculture fosters more adaptive, efficient, and economically viable food systems capable of thriving amid the pressures of a changing climate (Azhar *et al.,* 2025).

4. Nanotechnology in Agriculture

Nanotechnology is rapidly emerging as a groundbreaking force in agriculture, offering innovative solutions to longstanding challenges such as low nutrient use efficiency, pest management, and environmental sustainability. By manipulating materials at the nanoscale generally less than 100 nanometres, nanotechnology introduces unique physicochemical properties that enhance the functionality and effectiveness of agricultural inputs and processes (Shah *et al*.,2024). The application of nanotechnology in agriculture spans from nano-fertilizers and nano-pesticides, which improve nutrient delivery and pest control with minimal environmental impact, to nanosensors for real-time monitoring of soil and crop health, enabling precision farming. These advances hold promise for meeting the global demand for increased agricultural productivity while reducing resource wastage and ecological harm. As research and development progress, nanotechnology is poised to transform the entire agricultural value chain and contribute significantly to sustainable farming systems (Mobeen *et al.,* 2025).

4.1 Nano-Enabled Crop Protection and Nutrient Management

One of the most significant breakthroughs of nanotechnology in agriculture lies in the development of nano-encapsulated fertilizers and pesticides. Conventional fertilizers often suffer from low nutrient use efficiency, with a substantial portion lost to leaching and volatilization, leading to environmental pollution and economic loss. Nano-fertilizers provide controlled release and targeted nutrient delivery that aligns with plant uptake patterns, sharply improving efficiency and reducing waste. Similarly, nano-pesticides enhance solubility, stability, and target specificity, allowing reduced dosages and minimizing toxic effects on non-target organisms (Singh *et al.,* 2024). These nano-formulations leverage nanocarriers such as nanogels and emulsions to sustain the release of active ingredients, thereby improving pest and disease management while lessening ecological footprints. In parallel, nano-coatings and antimicrobial nanoparticles safeguard farming infrastructure and reduce crop spoilage by preventing microbial growth on surfaces such as greenhouse films and irrigation equipment. Together, these applications represent a leap forward in crop protection and nutrient management, promising higher yields and safer ecosystems (Ullah *et al.,* 2024).

4.2 Advanced Nano Sensors and Smart Delivery Systems for Precision Agriculture

Nanotechnology also revolutionizes monitoring and precision management in agriculture through smart nanosensors and delivery platforms. Nanosensors, including optical and electrochemical devices, provide real-time data on soil moisture, nutrient status, crop health, and pathogen presence, enabling early intervention and precision resource application. Integrated into IoT networks, these sensors facilitate high-resolution, site-specific decision-making essential to precision agriculture (Yadav and Yadav, 2025). Furthermore, advanced nano-porous materials, carbon nanotubes, and cellulose nanofibers act as smart carriers for the controlled and targeted delivery of agrochemicals, genes, and growth regulators. This tailored approach increases the efficacy of inputs, decreases environmental contamination, and supports sustainable intensification of farming. Emerging trends in nanotechnology also encompass seed priming with nanoparticles to accelerate germination and improve plant vigor, as well as innovative nano-enabled food packaging that enhances shelf life and safety. Collectively, these innovations are setting new standards for agricultural productivity, resilience, and sustainability, making nanotechnology a cornerstone of future smart farming (Shrestha *et al.,* 2021).

5.CRISPR and Genome Editing for Crop Improvement

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) and genome editing technologies have revolutionized the field of crop improvement by enabling precise, efficient, and targeted modifications of plant genomes. The CRISPR/Cas9 system utilizes a programmable RNA guide to direct the Cas9 enzyme to a specific DNA sequence, where it induces a double-stranded break that can be repaired to introduce mutations, insertions, or deletions (Ganger *et al.,* 2023). This transformative tool has accelerated plant breeding by allowing researchers to edit genes associated with vital traits such as yield, stress tolerance, disease resistance, and nutritional quality more rapidly and accurately than traditional breeding methods. As the global population grows and climate change imposes increasing stresses on agriculture, CRISPR-based genome editing holds immense promise for developing resilient crop varieties capable of sustaining food security in the future (Al-Dossary, 2025).

5.1 Precision Genome Editing for Enhanced Crop Resilience and Productivity

One of the most impactful advances in CRISPR technology has been its application to enhance crop resilience against biotic and abiotic stresses. By precisely knocking out susceptibility genes or introducing beneficial variants, scientists have engineered plants with improved resistance to pests, pathogens, drought, salinity, and extreme temperatures. For example, CRISPR has enabled the development of rice varieties with higher salt tolerance by targeting genes involved in stress response pathways (Singh *et al.,* 2022). Similarly, genome editing has accelerated breeding for disease resistance in diverse crops like tomato, wheat, and maize, significantly reducing yield losses. Importantly, CRISPR facilitates multiplex editing simultaneously modifying multiple genes to stack traits for complex stress tolerance and yield enhancement. This precision genetic improvement increases productivity while reducing dependence on chemical inputs such as pesticides and herbicides, aligning with sustainable agriculture goals (Manzoor *et al.,* 2023).

5.2 Advancements, Challenges and Prospects in CRISPR-Based Crop Improvement

Beyond trait improvement, advances in CRISPR methods, including base editing and prime editing, allow for highly specific modifications without introducing double-stranded breaks, reducing off-target effects and enabling refined control over plant genomes. Delivery systems such as viral vectors and nanoparticles continue to improve the efficiency and applicability of CRISPR across diverse crop species. However, challenges remain regarding regulatory frameworks, off-target mutations, and public acceptance, which vary across regions and influence the deployment of genome-edited crops (Saber Sichani *et al.,* 2023). Future research is focused on integrating CRISPR with systems biology and machine learning to predict editing outcomes and optimize gene targets. With ongoing progress, CRISPR is set to become a cornerstone technology in the next generation of crop breeding, offering transformative potential for climate-smart, sustainable agricultural systems that can adapt to ever-changing environmental conditions (Lee, 2023).

6. Biofertilizers and Biopesticides: Sustainable Alternatives to Chemicals

Biofertilizers and biopesticides are increasingly recognized as eco-friendly, sustainable alternatives to chemical fertilizers and pesticides, providing important solutions to some of agriculture's most urgent environmental and productivity challenges. These biological inputs harness natural processes to enhance nutrient availability and manage pests without the negative consequences posed by synthetic chemicals, such as soil degradation, water pollution, and biodiversity loss (Areej *et al.,* 2024). The contemporary move towards sustainable farming has accelerated in recent years, with biofertilizers and biopesticides contributing to climate-smart agriculture, protecting ecosystem health, and supporting stable crop production. Their adoption is now driven by advances in biotechnology and a collective drive to reduce carbon footprints, restore soil vitality, and through sustainable intensification, safeguard the future of agriculture for generations to come (Badiyal *et al.,* 2024).

6.1 Advances in Biofertilizer Technology and Soil Health

Recent developments in biofertilizer technology focus on improving soil fertility, nutrient cycling, and crop productivity through innovative microbial formulations. Biofertilizers typically contain living microorganisms such as Rhizobium, Azotobacter, cyanobacteria, and phosphate-solubilizing bacteria that colonize plant roots and promote natural nutrient uptake, especially nitrogen and phosphorus. By replacing or reducing synthetic fertilizer use, these products decrease environmental contamination and improve the long-term structure and organic content of soils (Yadav and Yadav, 2024). Next-generation biofertilizers incorporate consortia of multiple beneficial microbes, optimized for specific crops or soils, and may be combined with organic amendments like compost for enhanced effect. They also play crucial roles in mitigating abiotic stress such as drought or salinity by stimulating plant growth-promoting traits and improving water retention. The rise in research on biofertilizers from agricultural waste and advances in carrier technology have further improved their efficacy, stability, and ease of field application. Global trends show that biofertilizer use can enhance yields by 12–25% while building healthy soils and reducing environmental risks associated with conventional fertilization (Ntsomboh-Ntsefong *et al.,* 2025).

6.2 Innovative Biopesticides for Safe and Sustainable Pest Management

The evolution of biopesticides marks a fundamental shift in pest and disease control strategies toward more targeted and environmentally benign approaches. Unlike chemical pesticides, biopesticides are derived from natural sources such as bacteria, fungi, plant extracts like neem, or viruses, and act through multiple mechanisms: infecting or inhibiting pest development, repelling insects, or competing with pathogens (Kumar and Khurana, 2025). Recent advances include the development of microbial biopesticides formulated for disease-specific or localized pest pressures, as well as biochemicals and microbials employed in integrated pest management (IPM). These products can slow down resistance development among pest populations, protect beneficial insects and soil fauna, and dramatically reduce toxic residues in food and the environment. Innovations in peptide-based biopesticides, improved shelf-life, and compatibility with IPM systems have made them more reliable and economically attractive for farmers. By 2025, biopesticides are estimated to reduce pesticide use by up to 40% and are central to strategies that meet consumer demand for environmentally safe agricultural produce and compliance with global climate mitigation goals. While certain biopesticides may vary in efficacy depending on crop and target species, they represent a cornerstone in advancing sustainable agriculture and ensuring food safety (Harun-Ur-Rashid and Imran, 2025).

7. Vertical Farming and Controlled Environment Agriculture

Vertical farming is an innovative agricultural practice where crops are grown in vertically stacked layers instead of traditional horizontal fields. This method maximizes space use, often inside controlled indoor environments such as warehouses or specially designed buildings. Controlled environment agriculture focuses on creating optimal growing conditions by regulating factors like temperature, humidity, light, and nutrient supply. Together, vertical farming and controlled environment agriculture allow for higher crop yields, year-round production, efficient use of water and space, and protection from weather disruptions. These technologies are helping to address food security and sustainability challenges, especially in urban areas with limited arable land (Sowmya *et al.,* 2024).

7.1 Vertical Farming

Vertical farming is an advanced agricultural practice that involves cultivating crops in vertically stacked layers, often within controlled indoor environments. This system utilizes hydroponics, aeroponics, or aquaponics instead of traditional soil-based methods, making it highly efficient in terms of space and resource utilization. By growing plants in multi-tier structures, vertical farming maximizes productivity per square meter, which is particularly valuable in urban areas where arable land is limited. The integration of LED grow lights, automated irrigation, and climate control systems ensures optimal light, water, and nutrient delivery, resulting in faster growth and higher yields (Singh *et al.,* 2025). Additionally, vertical farms use up to 90% less water compared to conventional farming because water is recirculated in closed-loop systems. They also eliminate the need for pesticides due to controlled indoor environments, producing cleaner and safer food. This technology not only improves sustainability but also reduces transportation costs when integrated into urban food systems (Lahlou *et al.,* 2025).

7.2 Controlled Environment Agriculture (CEA)

CEA refers to the use of advanced technologies to create optimal growing conditions for plants in enclosed or semi-enclosed spaces. CEA involves precise regulation of temperature, humidity, CO_2 concentration, light intensity, and nutrient delivery to maximize crop growth and resource efficiency. Techniques such as hydroponics, aeroponics, and aquaponics are central to CEA, along with automated systems for irrigation, fertilization, and climate control. Sensors, IoT devices, and data analytics play a crucial role in real-time monitoring and management, enabling precision farming practices (Dsouza *et al.,* 2023). Moreover, by minimizing land use and water consumption, CEA supports sustainable agriculture and helps address challenges like land degradation and water scarcity. Its integration with renewable energy and AI-driven monitoring systems further enhances efficiency, making CEA an essential part of future food production strategies (Gan *et al.,* 2022).

8. Digital Farming and Big Data Analytics in Agriculture

Digital farming refers to the use of digital technologies to optimize and manage agricultural production. It involves collecting and analyzing data from various sources such as soil sensors, weather stations, satellite imagery, and drones. This data helps farmers make precise decisions about planting, irrigation, fertilization, and pest control to improve crop yields and resource efficiency. Big data analytics play a crucial role in digital farming by processing large volumes of information to provide actionable insights. Together, these technologies enable smarter, more sustainable agriculture by increasing productivity, reducing waste, and addressing challenges related to climate and resource limitations (Arijit *et al.,* 2025).

8.1 Digital Farming

Digital farming refers to the integration of digital technologies, sensors, and smart devices into agricultural operations to improve productivity, sustainability, and efficiency. It combines tools such as Internet of Things (IoT), GPS-guided machinery, drones, remote sensing, and mobile applications to collect and utilize real-time farm data. These technologies enable farmers to monitor soil conditions, weather patterns, crop growth, and pest infestations remotely, reducing reliance on manual inspections and guesswork. For example, soil moisture sensors and automated irrigation systems ensure precise water management, minimizing wastage and improving crop health (Paudel *et al.,* 2025). One of the major benefits of digital farming is precision agriculture, where inputs like water, fertilizer, and pesticides are applied at the right time and in the right quantity based on site-specific data. This reduces input costs, prevents resource depletion, and minimizes environmental pollution caused by over-application of chemicals. As a result, digital farming contributes to higher productivity, cost-effectiveness, and sustainability, which are crucial in meeting global food demands under climate change challenges (Papadopoulos *et al.,* 2024).

8.2 Big Data Analytics in Agriculture

Big Data Analytics in agriculture involves the processing and interpretation of vast amounts of data generated from digital farming tools, satellite imagery, weather stations, and market trends. These datasets include information on soil properties, crop performance, climate variables, pest dynamics, and consumer demand, which are analysed using advanced algorithms and machine learning models. Big data provides predictive insights that help farmers make informed decisions on crop selection, irrigation planning, pest control strategies, and harvesting schedules, thereby reducing risks and optimizing farm operations (Hussein *et al.,* 2025). Big data also plays a critical role in predictive and prescriptive analytics for agriculture. For instance, predictive models can forecast pest outbreaks or disease risks based on historical climate and crop data, while prescriptive analytics suggests the best course of action for mitigation. This approach also benefits the entire agri-value chain by improving market forecasting, reducing food waste, and supporting traceability and sustainability initiatives (Ahmed and Shakoor, 2025).

9. Soil Health Management

Soil health management focuses on maintaining and improving the quality and fertility of soil to support sustainable agriculture. Microbial innovations play a crucial role by using beneficial microorganisms that enhance nutrient cycling, suppress pathogens, and promote plant growth. These microbes help improve soil structure, increase nutrient availability, and reduce the need for synthetic chemicals. Soil amendments such as organic matter, compost and biofertilizers work together with microbial solutions to restore soil vitality, increase crop productivity, and protect the environment. This integrated approach supports long-term soil sustainability and resilience against stresses (Samantaray *et al.,* 2024).

9.1 Microbial Innovations in Soil Health Management

Microbial innovations have revolutionized soil health management by utilizing beneficial microorganisms to improve soil fertility, nutrient availability, and plant growth. Microbes such as nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azotobacter*), phosphate-solubilizing bacteria, mycorrhizal fungi, and plant growth-promoting rhizobacteria play a vital role in maintaining soil nutrient dynamics. These organisms convert unavailable nutrients into plant-usable forms, thereby reducing dependency on chemical fertilizers and enhancing sustainable agriculture. For example, biofertilizers enriched with microbial consortia promote biological nitrogen fixation, phosphorus solubilization, and potassium mobilization, leading to improved crop productivity (Ashoka *et al.,* 2025). Advanced microbial technologies also include biostimulants and microbial consortia that enhance soil enzymatic activity, organic matter decomposition, and root development. Additionally, certain microbes produce secondary metabolites that suppress soil-borne pathogens, reducing the need for chemical pesticides. Innovations such as nano-biofertilizers and microbial inoculants tailored for specific soil conditions have gained prominence for improving soil structure, water retention, and resilience to environmental stress. These microbial interventions not only boost productivity but also contribute to long-term soil health and ecological balance (Adedayo and Babalola, 2023).

9.2 Soil Amendments for Soil Health Improvement

Soil amendments refer to materials added to the soil to improve its physical, chemical, and biological properties. Common amendments include organic matter (compost, manure, biochar), lime, gypsum, and mineral additives, each playing a unique role in enhancing soil quality. Organic amendments, such as compost and green manure, improve soil structure, increase water-holding capacity, and stimulate microbial activity, making them essential for sustainable farming systems. Biochar, a carbon-rich material produced from biomass, has gained attention for improving nutrient retention, reducing soil acidity, and acting as a long-term carbon sink to mitigate climate change impacts (Ray *et al.,* 2025). Chemical amendments like lime and gypsum are used to correct soil pH and improve soil aeration in acidic or sodic soils. These amendments enhance nutrient availability and root penetration, leading to better crop growth. Modern innovations also include polymeric soil conditioners and nanomaterials, which improve soil aggregation and nutrient efficiency. Collectively, these strategies form a cornerstone for regenerative agriculture and sustainable soil management practices (Vinzant *et al.,* 2023).

10. Water-Smart Agriculture

Water-smart agriculture is an approach that focuses on using water efficiently and sustainably in farming to maximize crop production and protect natural resources. It emphasizes optimizing water use through techniques like drip irrigation, rainwater harvesting, and soil moisture monitoring. This practice also involves selecting drought-tolerant crops and improving water storage and distribution systems. Water-smart agriculture aims to increase resilience against climate change impacts and reduce water waste while ensuring long-term sustainability of agricultural production. It integrates social, economic, and environmental factors to support farmers in managing water resources responsibly (Frimpong *et al.,* 2023).

10.1 Drip Irrigation

Drip irrigation is a highly efficient water-saving technique that delivers water directly to the root zone of plants through a network of tubes, emitters, and valves. Unlike conventional flood irrigation, which leads to significant water loss through evaporation and runoff, drip systems minimize wastage by applying water in controlled quantities. This precision reduces water consumption by 30–70% compared to traditional methods while enhancing soil moisture consistency and nutrient uptake. Farmers can integrate fertigation systems with drip irrigation, allowing the delivery of fertilizers along with water, which ensures optimal nutrient availability and reduces leaching losses (Pal *et al.,* 2023). In addition to improving water-use efficiency, drip irrigation promotes uniform crop growth and higher yields, particularly in arid and semi-arid regions. It is highly suitable for horticultural crops, orchards, and vegetables, where precise water management is critical. The use of smart drip systems with sensors and automated controllers has further advanced this technology, enabling real-time monitoring of soil moisture and automated irrigation scheduling. These innovations contribute to sustainable water management and climate-resilient agriculture (Banik *et al.,* 2024).

10.2 Hydroponics

Hydroponics is a soilless farming method that involves growing plants in nutrient-rich water solutions or inert media such as perlite, coco peat, or rock wool. This system conserves up to 90% more water than conventional soil-based agriculture because water is recirculated and reused within the system. Hydroponics allows precise control over nutrient supply, pH levels, and environmental factors, resulting in faster growth rates and higher yields. It is especially beneficial for urban farming and regions with poor soil quality or limited arable land (Rajendran *et al.,* 2024). Modern hydroponic systems include nutrient film technique, deep water culture, and drip-based hydroponics, all of which are integrated with automation for monitoring and control. Hydroponics also reduces the need for pesticides since crops are grown in controlled environments, producing cleaner and safer food. When combined with renewable energy and vertical farming concepts, hydroponics supports sustainable, climate-smart agriculture with year-round production capability (Thapa *et al.,* 2024).

10.3 Aquaponics

Aquaponics combines aquaculture with hydroponics in a closed-loop system where fish waste provides nutrients for plant growth, and plants filter and purify the water for fish. This integrated system maximizes resource efficiency by recycling water and nutrients, reducing the environmental impact of both farming methods. Aquaponics requires only 10% of the water used in traditional farming, making it an excellent solution for water-scarce regions. It is also chemical-free because the use of synthetic fertilizers or pesticides can harm fish, ensuring organic and sustainable production (Alizaeh *et al.,* 2025). The dual production of fish and plants provides additional economic benefits and food security. Common crops grown in aquaponic systems include leafy greens, herbs, and fruiting vegetables, while fish species like tilapia and catfish are often cultivated. Advanced aquaponics systems integrate IoT sensors and AI algorithms to monitor water quality, nutrient levels, and temperature, ensuring optimal conditions for both plants and fish. This approach aligns with sustainable agriculture goals by reducing waste, conserving water, and providing diversified food production (Pena *et al.,* 2025).

11. Organic Farming

Organic farming is a sustainable agricultural system that avoids synthetic chemicals and relies on natural processes to maintain soil health and promote biodiversity. It emphasizes principles such as health, ecology, fairness, and care to produce nutritious food while protecting the environment. Innovations in organic farming include advanced techniques for soil fertility, pest control, and crop management that enhance productivity without harming ecosystems. Market trends show growing consumer demand for organic products driven by health awareness and environmental concerns, encouraging farmers to adopt organic practices for long-term sustainability and economic benefits (Akhuli, 2025).

11.1 Innovations in Organic Farming

Organic farming has evolved significantly with the introduction of innovative practices aimed at improving productivity, soil health, and pest management without relying on synthetic chemicals. Modern innovations include biofertilizers, biopesticides, and bio-stimulants that enhance nutrient availability and plant growth naturally. Microbial inoculants such as nitrogen-fixing bacteria, phosphate-solubilizing microbes, and mycorrhizal fungi are widely used to maintain soil fertility and boost crop yield sustainably. Techniques like crop rotation, intercropping, mulching, and green manuring have been optimized to prevent soil degradation and control weeds effectively (Kumar *et al.,* 2024). Technological advancements have also contributed to organic farming efficiency. The use of sensor-based irrigation systems, precision organic farming tools, and drones for monitoring crop health allows farmers to manage resources efficiently while adhering to organic standards. Additionally, vermicomposting and on-farm composting technologies provide nutrient-rich organic matter for improving soil structure. The integration of digital platforms for certification and traceability ensures transparency in the supply chain, enhancing consumer confidence in organic products (Narzari *et al.,* 2025).

11.2 Market Trends in Organic Farming

The global demand for organic products has witnessed exponential growth due to rising consumer awareness about health, sustainability, and environmental concerns. Market trends indicate a shift towards plant-based, chemical-free, and eco-friendly products, driving farmers to adopt certified organic farming practices. Developed regions like North America and Europe dominate the organic market, while countries in Asia-Pacific, including India, are emerging as significant players due to supportive government policies and export potential (Cam*,* 2023). Consumers are increasingly willing to pay premium prices for organic fruits, vegetables, dairy products, and grains, creating lucrative opportunities for farmers and agribusinesses. The rise of e-commerce platforms and direct-to-consumer models has further boosted organic product accessibility. Additionally, innovations in organic packaging and certification systems are strengthening consumer trust and regulatory compliance. Future trends suggest that organic farming will continue to expand, supported by sustainable practices, government incentives, and advancements in organic input technologies (Nedumaran *et al.,* 2020).

Conclusion:

Precision agriculture is revolutionizing crop management by leveraging IoT, drones, and AI to optimize resource efficiency, productivity, and sustainability. IoT sensors enable targeted irrigation, nutrient optimization, and continuous monitoring, while drones and AI facilitate high-resolution imaging, real-time crop monitoring, and automated decision support. Climate-smart agriculture integrates resilient crop and resource management with digital innovations to enhance productivity, adaptation, and mitigation. Nanotechnology offers breakthroughs in nano-fertilizers, nano-pesticides, and smart delivery systems for precision agriculture. CRISPR and genome editing enable precise crop improvement for enhanced resilience and productivity. Biofertilizers and biopesticides provide sustainable alternatives to chemicals, improving soil health and pest management. Vertical farming and controlled environment agriculture maximize space use and optimize growing conditions for higher yields and resource efficiency. Digital farming and big data analytics optimize agricultural production through data-driven insights and precision management. Soil health management focuses on microbial innovations and amendments to improve fertility and sustainability. Water-smart agriculture emphasizes efficient water use through drip irrigation, hydroponics, and aquaponics. Organic farming innovations and market trends drive sustainable practices and meet growing consumer demand for eco-friendly products.

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BACILLUS-BASED BIOCONTROL: AN ECO-FRIENDLY ALTERNATIVE TO CHEMICAL PESTICIDES

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Abstract:

Bacillus spp. is ubiquitous in diverse natural environments and represent a dominant component of the rhizomicrobiome, particularly within agricultural soils and plant root ecosystems. Scientific research has established that *Bacillus spp.* serves as highly effective biocontrol agents and plant growth-promoting rhizobacteria (PGPR), making them essential for sustainable agriculture. Their biocontrol efficacy is attributed to the production of a broad array of antimicrobial compounds—including lipopeptides, polyketides, and volatile organic compounds—as well as hydrolytic enzymes targeting phytopathogens. *Bacillus spp.* also activates plant defense mechanisms such as induced systemic resistance, enhancing the plant's resilience to diseases without the need for continuous chemical inputs. Beyond disease suppression, *Bacillus spp.* facilitates plant growth by producing phytohormones (e.g., auxins, gibberellins), improving the solubilization and availability of key nutrients like phosphorus and iron, engaging in nitrogen fixation, and stimulating robust root development. These multifaceted activities collectively increase crop tolerance to biotic and abiotic stresses and significantly reduce reliance on chemical fertilizers and pesticides. Commercialization of *Bacillus*-based biocontrol formulations is expanding globally, driven by their safety, environmental compatibility, and regulatory acceptance as eco-friendly biotechnological tools for agricultural production. The continued expansion of genomic, metagenomic, and phenotypic studies on *Bacillus spp.* is illuminating their diversity, mechanisms of action, and ecological functions, which supports the development of more targeted and high-performing products for modern agriculture.

Keywords: *Bacillus spp.* Chemical Pesticides, Biocontrol, Biocontrol Mechanism and Sustainable Agriculture.

1. Introduction:

Agriculture plays a significant role in food security, and maintaining crop health is important to support the needs of the global population. For the past century, chemical pesticides have been widely used to manage plant diseases and pests due to their ability to reduce pest populations and prevent yield losses. In conventional farming, various methods are employed to control diseases caused by phytopathogens. These include crop rotation over several years, maintaining field cleanliness, managing soil moisture, and selecting sites less favorable for pathogens. Farmers may also use moderately resistant crop varieties when available. Additional practices such as biofumigation, soil solarization, adding yard waste to soil, mulching with straw, growing cover crops, and applying chemical pesticides are utilized. (Hwang, 2002; Kim *et al.,* 2010). However, the extensive and indiscriminate use of synthetic pesticides has raised serious concerns regarding environmental safety, human health hazards, and ecological imbalance. Residues in food and water, pesticide resistance in pests, destruction of beneficial organisms, and soil degradation are some of the well-documented negative impacts. As a result, there is a pressing need to identify and adopt sustainable and eco-friendly approaches for plant disease and pest management (Shahid *et al.,* 2021; Khan *et al.,* 2022).

Among the various alternatives explored, microbial biocontrol agents (MBCAs) have emerged as promising tools in modern agriculture. These are naturally occurring microorganisms that suppress plant pathogens, enhance plant growth, and contribute to ecological balance without the adverse impacts associated with chemical pesticides. Within this group, members of the genus *Bacillus* occupy a central position due to their unique physiological and ecological traits (Wu *et al.,* 2015; Khan *et al.,* 2022 and Ramírez-Pool *et al.,* 2024). *Bacillus* species are Gram-positive, endospore-forming bacteria that are widely distributed in soil, water, plant rhizospheres, and even in extreme environments. Their ability to form spores enables them to survive harsh conditions, making them highly stable and reliable for field application. Unlike many other microbial BCAs, *Bacillus*-based formulations have the advantage of long shelf life, ease of mass production, and compatibility with existing agricultural practices. Several strains are already commercialized and widely used in organic and integrated farming systems (Dame *et al.,* 2021; Hirozawa *et al.,* 2023; Zhang *et al.,* 2023; Karačić *et al.,* 2024).

This chapter aims to provide a comprehensive overview of the role of *Bacillus* species in plant disease management. It will highlight their mechanisms of action, advantages over chemical pesticides, applications in modern agriculture, current limitations, and future prospects. By doing so, it emphasizes how *Bacillus*-based biocontrol agents can contribute significantly to the development of sustainable and eco-friendly agricultural systems worldwide.

2. *Bacillus spp.*: Diverse Biocontrol Strategies Against Plant Pathogens

Bacillus spp. known to employ a combination of direct and indirect strategies to suppress plant pathogens and promote plant health. These multifaceted biocontrol mechanisms include antibiosis, enzymatic activity, nutrient competition, siderophore production, induced systemic resistance (ISR), and plant growth promotion (Figure. 1 and 2) (Kulkova *et al.,* 2023; Salazar *et al.,* 2023; and Zhang *et al.,* 2023).

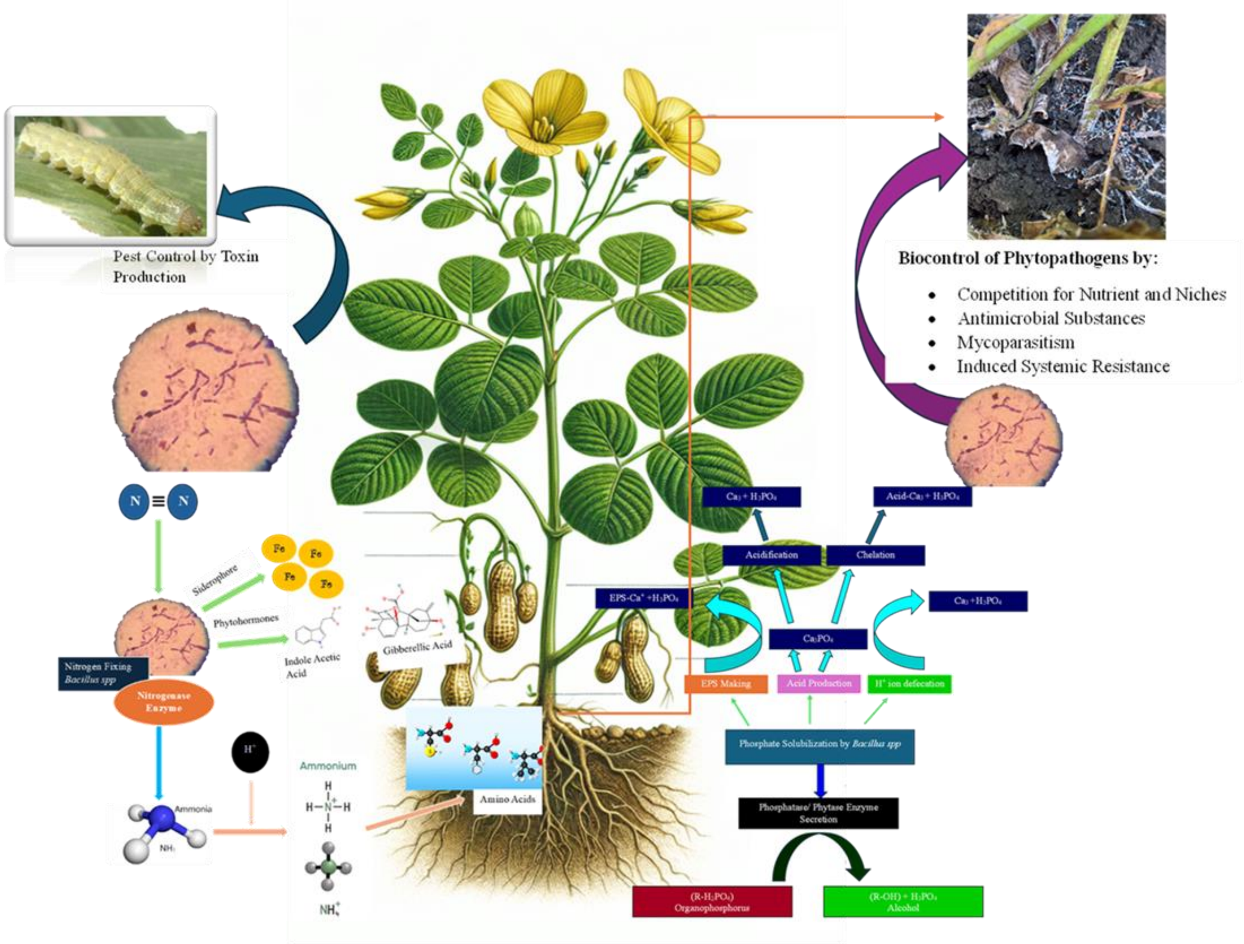

Fig. 1: *Bacillus spp.*: Diverse Biocontrol Strategies Against Plant Pathogens

2.1 Antibiosis: Production of Antimicrobial Compounds:

Bacillus spp. synthesizes a wide array of antimicrobial substances including antibiotics, lipopeptides (such as iturins, surfactins, fengycins), bacteriocins, and volatile organic compounds (VOCs) (Zhang *et al.,* 2023). These bioactive molecules can inhibit the growth of, or directly kill, plant pathogenic fungi, bacteria, and nematodes.

- **Lipopeptides:** Lipopeptides are one of the most important groups of bioactive compounds produced by *Bacillus spp* that play a central role in their ability to control plant pathogens. They are cyclic or linear molecules made of a lipid connected to a peptide chain, giving them both surface-active (surfactant) and antimicrobial properties.

The major families of *Bacillus* lipopeptides involved in biocontrol include surfactins, iturins, and fengycins (Shahid *et al.,* 2021; Valenzuela *et al.,* 2024).

- **Surfactins:** These are powerful biosurfactants with strong surface activity. Surfactins reduce surface tension and facilitate the spread of bacteria in the rhizosphere. They also have antimicrobial activity by disrupting pathogen cell membranes and have been shown to trigger induced systemic resistance (ISR) in plants, boosting their immune defense (Théatre *et al.,* 2021; Valenzuela *et al.,* 2024).
- **Iturins:** This family consists of cyclic lipopeptides with strong antifungal activity. Iturins insert into fungal cell membranes, causing pore formation and leakage of cellular , which leads to pathogen cell death. They are highly effective against a wide range of soil-borne fungal pathogens (Shahid *et al.,* 2021; Valenzuela *et al.,* 2024).
- **Fengycins:** These lipopeptides have antifungal properties, especially against filamentous fungi. Fengycins disrupt fungal membrane integrity and interfere with spore germination and hyphal growth. They also participate in eliciting plant defense responses (Rumyantsev *et al.,* 2024; Valenzuela *et al.,* 2024).

- **Polyketides and Dipeptides:**
  - Polyketides represent another important class of secondary metabolites produced by *Bacillus spp.,* which contribute significantly to their biocontrol potential. These are structurally diverse, complex natural products synthesized by polyketide synthases (PKSs), large multifunctional enzyme complexes. Polyketides act mainly against bacteria and fungi by disrupting their cell membranes or interfering with essential cellular functions. This helps in controlling both bacterial and fungal diseases in crops (Khan *et al.,* 2022).
  - Among the polyketides produced by *Bacillus*, three major groups are well-characterized: bacillaene, difficidin, and macrolactin (Aleti, 2016).
  - Similarly, Dipeptides are small peptides composed of two amino acids and are also produced as secondary metabolites by *Bacillus spp* which have shown antimicrobial effects, particularly by inhibiting the growth or development of specific plant pathogens such as fungi or bacteria (Dimkić *et al.,* 2017).
- **Volatile Organic Compounds (VOCs):** Volatile Organic Compounds (VOCs) are low-molecular-weight, easily vaporized metabolites produced by several beneficial microbes, including *Bacillus* spp. Unlike lipopeptides and polyketides, VOCs do not require direct contact between the producing bacterium and the pathogen. Instead, they diffuse through the air or soil pores, making them highly effective in suppressing pathogens at a distance (Grahovac *et al.,* 2023). Common VOCs produced by *Bacillus spp.* include acetoin (*B. subtilis*), 2,3-butanediol (*B. subtilis*, *B. amyloliquefaciens*), benzaldehyde, and various

alkanes and alkenes ((*Bacillus amyloliquefaciens* (ex Fukumoto) Priest, *B. subtilis* (Ehrenberg) Cohn and *B. thuringiensis* Berliner)), each contributing to direct effects on pathogens and/or indirect promotion of plant health (Grahovac *et al.,* 2023; Stocki *et al.,* 2025).

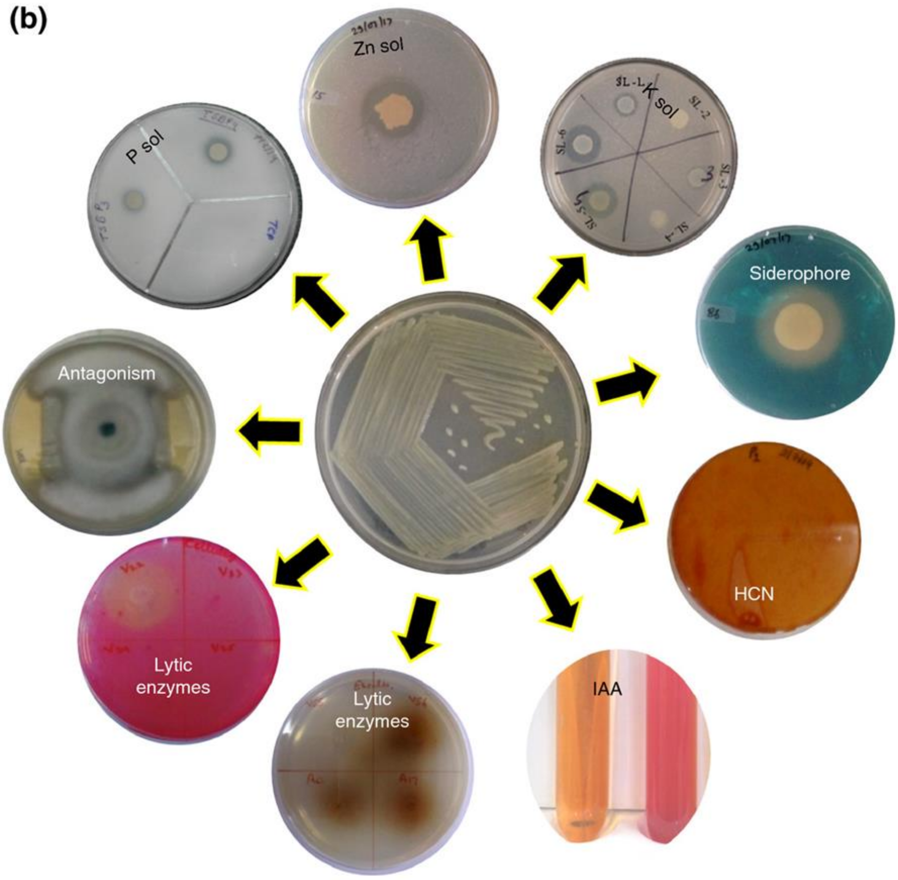

Fig. 2: Plant Growth-Promoting traits exerted by *Bacillus spp.* **(Saxena *et al.,* 2020)**

2.2 Hydrolytic Enzyme Secretion

One of the most important biocontrol strategies explored by *Bacillus spp.* is the production and secretion of extracellular hydrolytic enzymes. Phytopathogen cell walls are mainly composed of chitin, β-glucans, mannoproteins, and proteins, making them vulnerable to enzymatic hydrolysis. *Bacillus* spp. secretes a variety of hydrolytic enzymes that directly attack these structural polymers, thereby inhibiting pathogen growth, reducing infection, and facilitating the release of pathogen-derived elicitors that can trigger host plant defense responses (Lastochkina *et al.,* 2019; Khan *et al.,* 2022; Karačić *et al.,* 2024).

Major Hydrolytic Enzymes Produced by *Bacillus spp.*:

- **Chitinases:** Chitinases are hydrolytic enzymes produced by *Bacillus spp.* that degrade chitin, a key structural component of fungal cell walls (Veliz *et al.,* 2017). This enzymatic activity gives *Bacillus* strains significant biocontrol potential against plant pathogenic fungi and some pests (Raut *et al.,* 2021; Ajuna *et al.,* 2023).

- **β-1,3-glucanases:** β-1,3-glucanases are enzymes produced by *Bacillus spp.* that cleave β-1,3-glycosidic bonds in β-glucans—major structural components of many fungal cell walls. β-1,3-glucanases hydrolyse β-1,3-glucans in the cell wall of fungi, causing weakening and rupture. This leads to cell lysis or inhibiting growth of phytopathogenic fungi like *Fusarium, Alternaria, Bipolaris, Colletotrichum*, preventing disease progression in crops such as wheat, cucumber, pepper, and chili (Huyen *et al.,* 2024; Saini *et al.,* 2024).
- **Proteases:** Proteases hydrolyze proteins and peptide linkages, damaging the structural integrity of pathogen cell walls (especially in fungi) and membranes. This weakens or kills the invading pathogen, often in synergy with other cell-wall degrading enzymes like glucanases and chitinases (Ajuna *et al.,* 2023; Saini *et al.,* 2024).
- **Cellulases:** Cellulases hydrolyze β-1,4-glycosidic bonds in cellulose, weakening or lysing the cell walls of fungal pathogens such as *Colletotrichum*, *Botryosphaeria*, and other filamentous fungi (Kwon *et al.,* 2022; Yuan *et al.,* 2023).
- **Lipases:** Lipases hydrolyze the lipid bilayers in the cell membranes of fungi, bacteria, and nematodes, leading to leakage of cellular contents, loss of membrane function, and cell death (Ajuna *et al.,* 2023).

2.3 Competition for Nutrients and Space:

One of the most fundamental biocontrol mechanisms by which *Bacillus* species suppress plant pathogens is through competition for nutrients and ecological niches in the rhizosphere. The rhizosphere is a highly competitive environment where plants, beneficial microbes, and pathogens interact. Since both beneficial and pathogenic microorganisms depend on root exudates and soil nutrients for survival, rapid colonization and efficient nutrient utilization by *Bacillus spp.* limits the resources available to pathogens, thereby suppressing their establishment and growth (Ramírez-Pool *et al.,* 2024).

- **Siderophore Production:** Also, *Bacillus spp.* such as *Bacillus subtilis* CAS15 (Yu *et al.,* 2011) and *Bacillus subtilis* MF497446 (Ghazy & El-Nahrawy, 2021) are reported to produce siderophores, which are molecules that bind iron with high affinity. Iron is an essential but often limited resource in soil; siderophores function to sequester iron, thereby reducing its availability to other microorganisms, including potential pathogens, and may inhibit their growth (Karačić *et al.,* 2024).
- **Rapid Root Colonization and Biofilm Formation:** *Bacillus spp.* such as *Bacillus subtilis* HJ5 (Li *et al.,* 2013), *Bacillus pumilus* HR10 (Zhu *et al.,* 2020) known for rapid root colonization and biofilm formation which are crucial strategies employed to establish themselves on plant roots and protect plants from pathogens like

Verticillium dahliae, *Rhizoctonia solani* respectively. *Bacillus* cells rapidly attach to root surfaces through interactions with root exudates and surface molecules. This early colonization is vital for establishing a protective barrier against pathogen invasion (Ramírez-Pool *et al.,* 2024).

- **Utilization of Carbon and Other Nutrients:** *Bacillus spp.* is metabolically adaptable and capable of using a wide range of carbon compounds present in root exudates and the soil organic matter. This allows them to thrive in diverse soil environments and outcompete less adaptable pathogens (Karačić *et al.,* 2024).

2.4 Induced Systemic Resistance (ISR) by *Bacillus spp.*:

Several *Bacillus* strains have been reported to elicit Induced Systemic Resistance (ISR), a natural defense mechanism in plants. For instance, *Bacillus cereus* AR156 was shown to induce ISR against *Botrytis cinerea* in *Arabidopsis thaliana* (Nile *et al.,* 2017), while *Bacillus subtilis* K47, *Bacillus cereus* K46, and *Bacillus sp.* M9 were found to trigger ISR against Pepper golden mosaic virus in *Capsicum chinense* (Samaniego-Gámez *et al.,* 2023). ISR functions by priming the plant immune system, enabling it to mount faster and stronger responses upon pathogen challenge. Unlike direct antagonism, ISR provides broad-spectrum protection against bacteria, fungi, viruses, and insects without directly killing the pathogens. This mechanism represents a pivotal component of Bacillus-based biocontrol strategies.

2.5 Plant Growth Promotion by *Bacillus Species*:

Bacillus spp. are well-known as plant growth-promoting rhizobacteria (PGPR) that enhance plant development through various direct and indirect mechanisms. Their plant growth promotion ability complements their biocontrol functions, contributing to healthier, more strong crops. *Bacillus spp.* produce plant hormones such as indole-3-acetic acid (IAA), gibberellins, cytokinins, and abscisic acid, which regulate root and shoot growth, cell division, and differentiation, leading to improved plant vigor and biomass (Shahid *et al.,* 2021; Ramírez-Pool *et al.,* 2024). They solubilize and mobilize essential nutrients like phosphorus, potassium, and iron in the soil. For example, siderophore production enhances iron availability, while phosphate solubilization makes phosphorus accessible for plant uptake, boosting nutrition (Ramírez-Pool *et al.,* 2024). Some *Bacillus* strains, *B. pumilus* (Masood *et al.,* 2020) can fix atmospheric nitrogen, supplementing soil nitrogen and reducing the need for synthetic fertilizers.

3. Advantages of *Bacillus*-Based Biocontrol over Chemical Pesticides:

Bacillus-based biocontrol agents offer numerous benefits compared to traditional chemical pesticides, making them a desirable option for sustainable and environmentally friendly agriculture (Khan *et al.,* 2022).

1. Environmental Safety

- *Bacillus* based biopesticides are biodegradable and non-polluting, avoiding the soil, water, and air contamination commonly associated with chemical pesticides (Ramírez-Pool *et al.,* 2024).
- They do not accumulate harmful residues in the environment or food crops.

2. Reduced Human and Animal Toxicity

- *Bacillus* strains and their bioactive compounds are generally non-toxic to humans, animals, beneficial insects (like pollinators), and soil microorganisms, enhancing farmworker and consumer safety (Khan *et al.,* 2022).

3. Prevention of Resistance Development

- Unlike chemical pesticides targeting single pathogen sites, *Bacillus spp.* employs multiple mechanisms (antimicrobial metabolites, hydrolytic enzymes, ISR), reducing the chance of pathogen resistance.
- Use of *Bacillus spp.* as part of integrated pest management (IPM) minimizes chemical pesticide overuse and resistance problems (Khan *et al.,* 2022).

4. Soil and Plant Health Promotion

- *Bacillus spp.* enhances soil microbial diversity and fertility, improves nutrient cycling, and promotes plant growth, which chemical pesticides often disrupt.
- Biocontrol with *Bacillus spp.* supports sustainable agroecosystems with long-term productivity (Khan *et al.,* 2022).

5. Broad-Spectrum and Multifunctional Activities

- *Bacillus spp.* controls a wide variety of pathogens (fungi, bacteria, viruses, nematodes) and simultaneously promotes plant growth.
- This multifunctional capability reduces the need for multiple chemical inputs (Shahid *et al.,* 2021).

6. Compatibility with Organic Farming

- *Bacillus spp.* biocontrol agents meet organic certification standards, while many chemical pesticides are prohibited in organic agriculture (Shahid *et al.,* 2021).

7. Cost-Effectiveness and Sustainability

- Although some biopesticides may have higher initial costs, their environmental and health benefits, coupled with improved soil and plant health, make them economically sustainable over the long term (Ramírez-Pool *et al.,* 2024).

4. Applications of *Bacillus*-Based Biocontrol in Modern Agriculture

Bacillus spp. has diverse and expanding applications in modern agricultural practices as eco-friendly biocontrol agents and plant growth promoters. Their multifunctional roles support sustainable crop production, reduce reliance on chemical pesticides, and enhance resilience against biotic and abiotic stresses (Shahid *et al.,* 2021; Khan *et al.,* 2022 and Ramírez-Pool *et al.,* 2024).

1. Disease Management

- **Control of Soil-Borne and Foliar Pathogens:** *Bacillus spp.* effectively suppresses fungal diseases like *Fusarium* wilt, *Botrytis cinerea*, Anthracnose, and Phytophthora blight, as well as bacterial diseases by producing antimicrobial compounds and enzymes (Khan *et al.,* 2022 and Ramírez-Pool *et al.,* 2024).
- **Postharvest Disease Suppression:** *Bacillus spp.* are used to manage fruit and vegetable spoilage, reducing losses caused by pathogens such as *Penicillium* and *Botrytis* during storage and transport (Khan *et al.,* 2022 and Ramírez-Pool *et al.,* 2024).

2. Seed Treatment and Soil Amendment

- Application of *Bacillus spp.* as seed coatings improves germination, seedling vigor, and initial root colonization, providing early disease protection and nutrient support (Khan *et al.,* 2022 and Ramírez-Pool *et al.,* 2024).
- Soil inoculation with *Bacillus spp.* enriches the rhizosphere microbiome, promotes nutrient cycling, and suppresses soil pathogens, resulting in healthier growing conditions (Khan *et al.,* 2022 and Ramírez-Pool *et al.,* 2024).

3. Plant Growth Promotion and Stress Tolerance

- *Bacillus spp.* enhances plant growth by producing phytohormones, solubilizing nutrients, and inducing systemic resistance, helping crops tolerate stressors such as drought, salinity, and heavy metals (Shahid *et al.,* 2021).

4. Integrated Pest Management (IPM)

- *Bacillus* formulations are integrated with other biological agents, agronomic practices, and minimal chemical inputs to design sustainable IPM programs, reducing chemical pesticide dependence and environmental impact conditions (Khan *et al.,* 2022 and Ramírez-Pool *et al.,* 2024).

5. Organic Farmingaa

- *Bacillus spp.* biocontrol agents meet organic certification standards, offering organic farmers effective tools for disease and pest management without synthetic chemicals conditions (Khan *et al.,* 2022).

6. Commercial Products and Formulations

- Various *Bacillus*-based biopesticides, biofertilizers, and biostimulants are commercially available worldwide, formulated as powders, granules, liquids, or encapsulated products suitable for foliar sprays, soil treatment, or seed dressing (Karačić *et al.,* 2024).

5. Current Limitations of *Bacillus*-Based Biocontrol in Agriculture:

1. **Inconsistent Field Performance:**
   The efficacy of *Bacillus* biocontrol agents can vary widely under different environmental conditions (soil types, climate, crop species), making field results sometimes unpredictable compared to controlled lab settings (Wu *et al.,* 2015).
2. **Strain Selection and Characterization Challenges:**
   Identifying and developing highly effective, stable *Bacillus* strains with consistent biocontrol activity and plant growth promotion traits remain complex and resource-intensive (Wu *et al.,* 2015; Ramírez-Pool *et al.,* 2024).
3. **Formulation and Shelf-Life:**
   Ensuring long shelf-life, stability, and viability of *Bacillus* formulations in commercial products is challenging. Factors like moisture, temperature, and storage conditions affect product quality (Wu *et al.,* 2015; Ramírez-Pool *et al.,* 2024).
4. **Regulatory and Market Barriers:**
   Biopesticides face stringent and varied regulatory frameworks globally, which can limit commercialization, market entry, and farmer adoption. Awareness and acceptance of biocontrol alternatives are still growing (Wu *et al.,* 2015).
5. **Limited Understanding of Microbe-Plant-Pathogen Interactions:**
   Although mechanisms of *Bacillus* biocontrol are increasingly understood, the complex tripartite interactions among *Bacillus*, plants, and pathogens require deeper research for precise and optimized applications (Wu *et al.,* 2015; Zhang *et al.,* 2023).

6. Future Prospects of *Bacillus*-Based Biocontrol in Agriculture:

1. **Strain Improvement through Genetic and Synthetic Biology:** Advances in genome editing, molecular breeding, and synthetic biology allow engineering *Bacillus* strains for enhanced antimicrobial production, stress tolerance, and colonization ability (Wu *et al.,* 2015).
2. **Multi-Strain and Consortia-Based Products:** Developing formulations combining multiple *Bacillus* strains or complementary beneficial microbes can increase spectrum and stability of biocontrol and growth promotion (Ji *et al.,* 2022).
3. **Advanced Formulation Technologies:** Nanotechnology, microencapsulation, and biofilm-based formulations promise to improve *Bacillus* survival, targeted delivery, and controlled release in diverse agricultural environments (Wu *et al.,* 2015; Ramírez-Pool *et al.,* 2024).
4. **Integration with Precision Agriculture:** Combining *Bacillus* biocontrol with sensors, drones, and AI-driven monitoring can optimize application timing and doses, maximize efficacy and minimize costs (Ramírez-Pool *et al.,* 2024).

5. **Expanded Crop and Stress Targets:** Ongoing research explores *Bacillus* use against new pathogens, pests, and abiotic stresses (e.g., salt, drought), widening their agricultural applicability ((Khan *et al.,* 2022 and Ramírez-Pool *et al.,* 2024).
6. **Increased Adoption and Policy Support:** Strengthening farmer education, subsidies, and regulatory harmonization can boost acceptance and use of *Bacillus* biocontrol in mainstream farming (Pieterse *et al.,* 2014).

Conclusion:

Bacillus spp. have emerged as vital agents in sustainable agriculture due to their dual ability to control plant pathogens and promote plant growth. They protect crops by producing antimicrobial compounds such as antibiotics, lipopeptides, hydrolytic enzymes, and volatile organic compounds, which inhibit a broad spectrum of pathogens. Additionally, *Bacillus spp.* enhances plant health indirectly through mechanisms like induced systemic resistance (ISR), competition for nutrients and space, and biofilm formation on plant roots. Their plant growth promotion functions involve nitrogen fixation, solubilization of phosphorus and potassium, phytohormone production, and improvement of stress tolerance.

Despite some challenges such as inconsistent field performance, formulation stability, and regulatory hurdles, ongoing advances in genomics, synthetic biology, and formulation technologies hold promise to overcome these limitations. The integration of Bacillus-based biocontrol into precision agriculture and combined microbial consortia approaches is expected to boost efficacy and adoption.

Overall, *Bacillus spp.* represents powerful and eco-friendly tools for reducing chemical pesticide use, ensuring crop protection, enhancing yields, and supporting resilient agroecosystems. Their broad-spectrum biocontrol and plant growth-promoting traits position them at the forefront of environmentally sustainable modern agricultural practices.

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SOIL QUALITY UPGRADING BY ORGANIC FARMING

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Abstract:

Soil is the backbone of agriculture, which provide us food, feed, fruit, fibre and fuel. Soil quality represents the soil as a finite non-renewable and dynamic living resource. Soil health or Soil quality in Asia, shows detrimental outcome on soil quality turnout from nutrient imbalance in soil due to extreme usage of inorganic fertilizers. A quality soil includes interactive attributes of soil physical, chemical and biological quality. Organic Farming is an agricultural production system which stop the use of inorganic fertilizers, pesticides, growth regulators etc., it is based upon organic material relay upon FYM, Compost, Green manure, Vermicompost and Biofertilizers. Soil quality upgrading in India was poor, due to deficit of organic carbon in the soil, poor usage of organic manures and also accelerate decomposition of organic matter. The government is implementing various schemes, missions and projects such as National Programme of Organic Production and National Project on Organic Farming improved soil organic matter levels leads to better crop yield.

Keywords: Soil Quality, Organic Farming and Nutrient Management

Introduction:

Agriculture as a way of life with animal husbandry is often an integral part of the system. Organic farming system is not new for India; it being followed from ancient time. The importance of organic manure in agriculture is known since ancient times. Organic farming is a technology which foreclose or largely scoop the use of synthetic input (such as fertilizers, pesticides, fungicides, weedicides, etc.) and to the supreme limit agreeable trust upon crop rotation, crop residues, animal manures, off-farm organic waste etc. Early 1950's in India all agricultural cultivate was organic. Organic farming is also known as eco-friendly farming or biological farming.

In India, in 2016, the northern state of Sikkim achieved its object of adapting to 100% organic farming (Source: "Sikkim makes an organic shift", Times of India. 7th May 2010). Other states of India, including Kerala, Mizoram, Goa, Rajasthan, and Meghalaya have also declared their goals to shift to totally organic cultivation farming. Andhra Pradesh is also forwarding organic farming, notably Zero Budget Natural Farming (ZBNF), which is a form of renewing agriculture.

More than 30 per cent of world's organic producers are in India

As of report on 21st February,2018, India has the largest number of organic farmers in the world and component, more than 30% of organic farmers globally (www.down to earth.org.in/agriculture,2018). India has 835,000 certified organic producers (Source: FiBL survey, 2019).

How much area in India is under organic farming? As of March 2020, 2,780,000 hectares were under certified organic farming in India, about 2 % of India's 140.1 M. ha net sown area (Council on Energy, Environment and Water, 2021, New Delhi, India).

Long term fertilizer experiments (LTFE) started in 1970 clearly signified that application of fertilizer along with organic manures is only renewable for production and nutritive security (Goswami,1998).

Organic manures as a source of plant nutrients vis-à-vis chemical fertilizers declined significantly. Organic farming means in the spirit of organic relationship between soil, water and plants, between soil, soil microbes and waste products. Organic farming keeps away from chemical fertilizers and pesticides, organic increase soil fertility, balance insecta population and reduce air, soil and water pollution. In India broad area of cultivated land is under rainfed, tribal and hilly area where there is very negligible or no use of chemical fertilizers hence their area may be brought under organic farming.

Cow dung

Composition

- **Water**: about 80% water
- **Undigested plant matter:** made up of cellulose, hemicelluloses, and lignin
- **Minerals**: contains calcium, magnesium, potassium, nitrogen, phosphorus, zinc, iron, manganese, copper, cobalt, and sulfur
- **Microorganisms**: contains bacteria, yeast, and protozoa

NPK Values of Animal Manures

	Nitrogen %	Phosphorus %	Potash %
Cow Manure	0.6	0.4	0.5
Horse Manure	0.7	0.3	0.6
Pig Manure	0.8	0.7	0.5
Chicken Manure	1.1	0.8	0.5
Sheep Manure	0.7	0.3	0.9
Rabbit Manure	2.4	1.4	0.6

https://www.allotment-garden.org...

Animals are essential part of organic farming systems

Farm manure - one of the most important agricultural by products

Compost results in humus formation and promotes good soil structure

In organic farming mode, it becomes necessary to adopt to an expertise to produce surplus food grains to feed the huge population of the country and at the same time secure the fertility of soil and produce food which are safer, healthier and tastier.

In 2007 the United Nations (FAO) said that organic agriculture often leads to higher prices and consequently a better income for farmers, so it must be promoted. Permanent Manurial Experiments conducted at Coimbatore (Tamil Nadu) it has been observed that continuous addition of cattle manure for 68 years resulted in significantly buildup of Zn, Mn, Cu etc.in the soil (Kurumthottical,1995). Selenium an antioxidant nutrient that safeguard against cancer and heart disease is also higher in organic foods, Calcium, Boron, lithium, Iron etc. are all found more in organic foods compared to ordinary foods (Jha,2003).

Humic and non-humic compounds collectively make up humus

Biofertilizers have been recognized as lively component of organic farming. Rhizobium, Azotobacter, Azospirillum, BGA, Azolla, PSB, VAM are the major biofertilizers available in Indian Agriculture and Biological nitrogen fixation (BNF) process does not affect environmental pollution and renewable (Shankaran, 1993). The maximum contribution of BNF to agriculture is derived from the symbiosis between legumes and species of Rhizobium. Inoculation of pulses is long evidenced and successful practice to assure sufficient N nutrition in place of fertilizer N in most of the soil. In most of the studies on biofertilizer, there is saving of fertilizer N to the tune of 15-25 kg N/ha (Dixit *et al,* 1992; Patil *et al,* 1992; Raut *et al,* 1995; Agarkar, 2002 and Singh,1993). Incorporation of short duration kharif legumes green gram, black gram and soybean increased not only yield but also made available nutrients to succeeding crops (Shinde *et al.,* 1966).

The era of green revolution resulted in glorious achievement in the food grain production. The agriculture production has been improving using inorganic fertilizers, pesticides, fungicides and surface and ground water resources pertaining to producing more from unit piece of land. According to Bhattacharya and Chakraborty (2005). As demand for food increases, farmers are cleaning new land resulting in deforestation, cultivate of pasture and soil degradation. Agriculture is one of the most considerable factors contributing to the economic progress of India.

Impact of Green Revolution

i. Affects Physical, Chemical and Biological properties of soil.
ii. Poor in soil fertility.
iii. Poor aeration and decrease water holding capacity of soil.
iv. Widespread occurrence of micronutrient deficiencies in soils.
v. Reduction in population and activity of microbes.
vi. Reduction in drought tolerance of crops.
vii. Killing of beneficial insects.
viii. Pollution of soil and water.
ix. Building up of newer pests and pathogens.
x. Affects health of the farmers on application of chemicals.
xi. Residues of pesticides in food chain which affects the health of consumers.
xii. Increase in cost of production.

Out of the 329 million hectares of India's geographical area, about 114 million hectares are under cultivation. Area affected by soil degradation is 187.9 million hectares (57.1%) of the total geographical area. Deterioration in the form of water erosion (148.9 million hectare), Wind erosion (13.5 million hectare), Chemical degradation like sulphate attack, leaching, alkali -silica reaction (13.8 million hectare), Physical degradation like water logging, freezing, fire, soil cracking and shrinkage (11.6 million hectare) and biological degradation like human and animal waste, hospital waste, industrial chemicals. The toxic properties of fertilizers possess potential hazard to human health. Respiratory symptoms, such as coughing, wheezing, asthma, lung cancer, are observed among prone to such infectious fertilizers. Excess and indiscriminate utilize of inorganic fertilizer has deteriorated soil badly with deficiency of macro nutrients and micronutrients.

The World of Organic Agriculture
(2021)

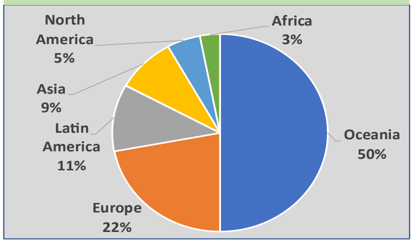
190 countries
74.9 M. ha farm area (1.6%)
30.0 M. ha wild harvest
3.1 Million producers

Largest countries
- 35.7 M. ha Australia
- 4.5 M. ha Argentina
- 2.7 M. ha Uruguay
- 2.6 M. ha India

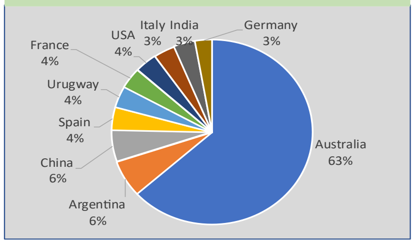
120 billion Euros (US$ 132 billion) Global market
- 41 % USA
- 37% EU
- 8.5% China

Where,
M. ha : Million hectare

Share of Continents in area %



10 largest countries in area (% share)



Principles of Organic farming

i. No Chemical Fertilizer.

ii. No Use of Herbicide.

iii. No Use of Pesticides.

iv. Maintenance of Healthy Soil (Source: Sahai,2011).

Components of Organic Farming

i. Organic Manure
ii. Biological Pest Management
iii. Non-chemical Weed Control
iv. Agronomical Practices
v. v. Alley Cropping (Source: Sahai,2011).

Organic manures commonly use in organic farming

i. Farmyard Manure
ii. Green manure
iii. Vermi-compost
iv. Crop residues
v. Bio-fertilizers

Major Sources of organic inputs in India

i. Livestock. ii. Crop residues.iii. Biogas slurry. IV. Boi-fertilizers. V. Green manure. vi. City refuse. vii. Bio-pesticide (Source: Bhattacharya,2006).

Crops under Organic Farming-India

i. Cereals and Commercial crops: Rice, Wheat, Cotton and Sugarcane.
ii. Pulses: Red gram and Black gram.
iii. Oilseeds: Sesame, Castor, Sunflower and Mustard.

iv. Fruits: Mango, Litchi, Banana, Pineapple and Citrus.
v. Plantation Crops: Tea and Coffee.
vi. Spices: Cardamom, Ginger, Turmeric, Clover, Black pepper and Chili.
vii. Vegetables: Okra, Brinjal, Onion, Tomato and potato
(Source: Sivamurugan A.P. *et.al.*2012).

Advantages of Organic Farming

i. Conservation of Natural resources (Soil and Water etc.)
ii. Enhances Soil Productivity.
iii. Prevent damage to eco-system (Soil, Water and Atmospheric pollution).
iv. Reduce prevent entry of toxicants into the food chain.
v. Promote exports of organic foods and fibre.
vi. Generates on farm rural employment in developing countries
(Source: Rathinasamy and Saliha,2014).

Constraints of Organic Farming

i. Lack of documentation on organic farming.
ii. Lack of market information.
iii. Lack of proper infrastructure.
iv. Limited domestic market.
v. Less scope in small farm holdings.
vi. Lack of awareness among most of the farmers.
vii. More suited for fruits, vegetables and flowers
viii. (Source: Sivamurugan A.P. *et.al.*2012).

Implementation

Government of India is upgrading organic farming through various Schemes like National Project on organic production (NPOP), The government of India is implementing a new scheme, "National Project on Organic Farming" for production, promotion and market development of organic farming (NPOF). National Horticulture Mission (NHM). Network project on organic farming of Indian council of Agricultural Research (ICAR) and some other schemes.

Conclusions:

The organic manure is the life of soil and if neglected the fertility of soil would not be conserved. Soil quality management in India there is a deficit of organic carbon in the soil because of poor use of organic manures. Organic manures can generate a favourable air and water regime around plant roots and act as carriers of some micronutrients besides its influences on the microbial activities in the soil. Improper and continuous use of inorganic fertilizers and pesticides etc. in the soil throughout the years resulted in certain deleterious effects on soil quality leading to decline in productivity of crops. Organic farming will make better the fertility level of soil as follows, helping the yield of crops and improves the nutrient-rich soil.

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POTENTIALS AND OPPORTUNITIES OF AGRO-FORESTRY UNDER CLIMATE CHANGE SCENARIO

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Abstract:

India, with its burgeoning population projected to reach 1.67 billion by 2050 and declining per capita land availability, faces immense pressure to sustainably increase agricultural productivity. Traditional land-use practices are no longer sufficient to meet the growing demands for food, fodder, fuel, fiber, and timber. The agri-horti-silviculture system, a form of integrated agroforestry, offers a sustainable solution by synergizing agriculture, horticulture, and forestry components within a single ecosystem. This system utilizes underused interspaces during the early growth stages of perennial trees to cultivate intercrops, thereby enhancing land productivity, improving soil health, and diversifying farmers' incomes. The practice promotes ecological balance through nutrient cycling, carbon sequestration, erosion control, and biodiversity conservation. India exhibits significant agroforestry potential across its 15 agro-climatic zones, with varying extents and types of systems such as agri-silviculture, agri-silvi-pasture, and alley cropping. The paper highlights major advantages, including enhanced resource efficiency, economic resilience, and environmental restoration, while also addressing prevailing constraints like limited awareness, poor market access, policy gaps, and technical challenges. To maximize the benefits of agroforestry, strategic interventions such as improved policy frameworks, selection of suitable tree ideotypes, capacity building, and innovative enterprise integration (e.g., bamboo-based industries, fruit processing units) are essential. Agri-horti-silviculture thus represents a climate-resilient, productive, and environmentally sustainable approach to future farming systems in India.

Key words: Agroforestry, Components, Climate Change, Advantages and Disadvantages

Introduction:

The present population of India is 1.45 billion and it is likely to reach 1.67 billion by 2050 and per capita land availability in India is estimated to be around 0.1097 hectares (Anon., 2024). The current land use system with separate allocation to agriculture, horticulture and forest are inadequate to meet the ever increasing demand for diversified products such as food, fiber, fodder, fruit, fuel, timber etc. During the early time, non-bearing phase of fruit trees, when their canopy is still small, the vacant space between the trees offers an opportunity to cultivate harmless intercrops such as fodder, vegetables, agronomic crops, pulses (especially legumes), or even short-duration timber trees. This approach, known as agri-horti-silviculture system, not only provides additional income for orchardists but also helps maintain soil health by improving its physical and chemical properties (Dhillon *et al.,* 2012). An efficient agroforestry system provides an economical and ecologically feasible opportunity for large scale diversification in agriculture on one hand and environmental amelioration on the other (Nayak *et al.,* 2014). Intercropping in horti-silviculture systems is crucial for generating early and consistent returns during the unproductive phase of long-term tree plantation. Additionally, on-farm timber plantations can provide broader environmental benefits, such as participation in carbon trading programs (Pandey, 2007 and Dogra, 2007). Tree-based intercropping systems can also enhance economic diversification, offering both short and long term products from both agricultural and tree plantations. The selection of intercrop species must, however, be carefully considered to minimize competition and maximize returns, ensuring that it is tailored to the specific site conditions. Given these considerations, alternative land use practices such as agri-horti-silviculture system are increasingly necessary in response to population pressure and rising demand for diversified products.

The agri-horti-silviculture system is an integrated approach to agricultural production that combines agriculture (agri), horticulture (horti), and silviculture (forestry) practices within a single ecosystem. This system aims to enhance crop productivity while promoting ecological sustainability and biodiversity. In an era where the pressures of climate change, soil degradation, and growing food demands are becoming more intense, this multifaceted approach offers an effective solution to ensure food security and sustainable land use. The concept of agri-horti-silviculture involves the strategic integration of different land-use practices to optimize the use of available resources. By combining crop farming (agriculture), fruit and vegetable production (horticulture), and tree plantation (silviculture), this system maximizes the productivity of the land while maintaining ecological balance. The presence of trees helps in improving soil fertility through nutrient cycling, conserving moisture, preventing soil erosion, and enhancing biodiversity. One of the core benefits of this system is its ability to diversify sources of income for farmers. With crops, fruits, and timber or fuelwood production, farmers are less vulnerable to market fluctuations or environmental challenges. Additionally, the system encourages a symbiotic relationship between different types of plants crops can benefit from the shade and root interactions with trees, while trees can thrive in the nutrient-rich soil enhanced by crops and horticultural practices.

This integrated approach also addresses several pressing environmental issues, such as land degradation, water scarcity, and the loss of biodiversity, all while contributing to higher yields and improved economic returns for farmers. Moreover, by reducing dependency on chemical inputs and enhancing organic matter content in the soil, it supports the principles of organic farming and sustainable agricultural practices.

In summary, the agri-horti-silviculture system is a forward-thinking solution that promotes the synergy between various agricultural components, leading to increased crop productivity, better resource management, and greater environmental sustainability. As global agricultural systems continue to evolve, this integrated approach is gaining traction as a vital strategy for improving productivity while safeguarding the planet's resources. Improving crop productivity through the Agri-Horti-Silviculture System is a sustainable and integrated approach to agriculture that combines three key practices: Agriculture, Horticulture, and Silviculture (the cultivation and management of trees). This system seeks to optimize land use, enhance biodiversity, improve soil health, and increase overall productivity by blending crops, fruit-bearing trees, and forestry practices in a synergistic manner.

Key Components:

Agriculture: Involves the cultivation of food crops such as cereals, pulses, and vegetables. It typically focuses on short-term, high-yielding crops that can provide immediate returns.

Horticulture: The branch of agriculture that focuses on growing fruits, vegetables, nuts, seeds, herbs, sprouts, mushrooms, algae, and non-food crops like flowers and grass. This adds economic value and diversity to the farming system.

Silviculture: The cultivation of trees and management of forests to meet various needs, including timber, fuelwood, fodder, and environmental services such as carbon sequestration and biodiversity conservation. Silviculture practices help in maintaining long-term productivity and ecological balance.

The largest geographical area is under Eastern Plateau and Hill Region zone (40.525 M ha) followed by Southern Plateau and Hill Region (39.294 M ha) zone and smallest zone is The Island Region (0.785 M ha). Coming to agroforestry area higher under Eastern Plateau and Hill Region zone (4.292 M ha) followed by Northern Himalayan Region (4.096 M ha) and lower agroforestry area is covered Island Region (0.019 M ha). Coming to agroforestry area under percentage is higher under Upper Gangetic Plains Region (15.55 %) followed by West Coast

Plains and Hill Region (13.96 %) and Gujarat Plains and Hill Region (13.76 %). Whereas, lowest agroforestry area is under Island Region (2.42 %).

Table 1: Extent of agroforestry systems in 15 agro climatic zone-wise

Sl. No.	**Agro climatic zones**	**Geographical area (M ha)**	**Agroforestry area (M ha)**	**Agroforestry area (%)**
1	Northern Himalayan Region	32.968	4.096	12.42
2	Eastern Himalayan Region	28.422	1.088	3.83
3	Lower Gangetic Plains Region	6.238	0.802	12.86
4	Middle Gangetic Plains Region	16.526	1.304	7.89
5	Upper Gangetic Plains Region	14.367	2.234	**15.55**
6	Trans Gangetic Plains Region	11.750	1.143	9.73
7	**Eastern Plateau and Hill Region**	**40.525**	**4.292**	10.59
8	Central Plateau and Hill Region	37.435	1.924	5.14
9	Western Plateau and Hill Region	32.539	1.556	4.78
10	Southern Plateau and Hill Region	39.294	2.976	7.57
11	East Coast Plains and Hill Region	19.948	2.230	11.83
12	West Coast Plains and Hill Region	11.69	1.632	13.96
13	Gujarat Plains and Hill Region	18.673	2.570	13.76
14	Western Dry Region	17.587	0.431	2.45
15	The Island Region	0.785	0.019	2.42
Total/percentage		**328.747**	**28.427**	**8.65**

Arunachalam *et al.,* 2022

Distribution of the agroforestry system in different region of the country, blue colour indicates agri--silvi-pasture system distribution in different region, green colour indicates agri-silviculture system distribution in different region and red colour indicates silvi-pasture system distribution in different region of country.

Major agro-forestry systems practiced in India

1. **Agri-silviculture: -** Agri-silviculture is an agroforestry practice that involves the simultaneous cultivation of agricultural crops and trees on the same piece of land. Ex. trees + crops.
2. **Boundary plantation:** - Boundary plantation involves planting trees along the edges of agricultural fields, roads, or property lines. Ex. tree on boundary + crops.

3. **Block plantation: -** Block plantation is an agroforestry practice where trees are planted in compact, contiguous blocks, typically covering areas larger than 0.1 hectare. Ex block of tree + block of crops.
4. **Energy plantation:** - Energy plantation refers to the cultivation of specific tree and shrub species grown primarily for the production of biomass intended for energy generation. Ex. trees + crops during initial years.

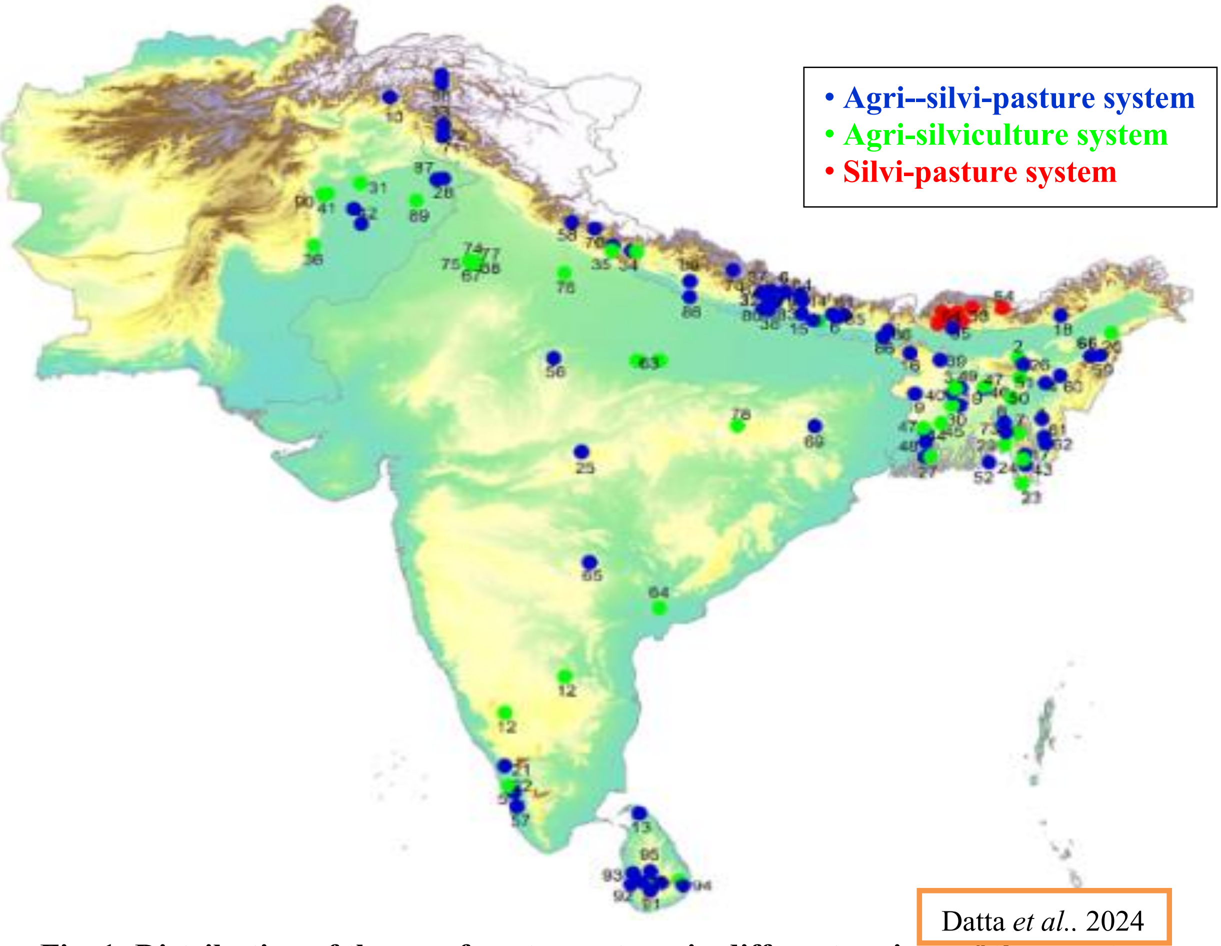


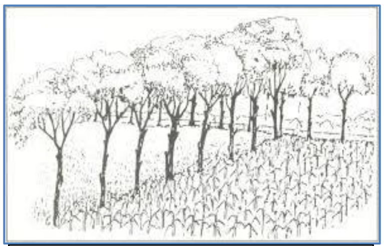
Fig. 1: Distribution of the agroforestry systems in different regions of the country

5. **Alley cropping:** - Alley cropping is an agroforestry practice that involves planting rows of trees or shrubs to create alleys within which agricultural or horticultural crops are cultivated. Ex. hedges + crops.
6. **Agri-horticulture**: - Agri-horticulture is an integrated agricultural practice that combines the cultivation of fruit trees and agriculture crops with traditional crop farming. Ex. fruit trees + crops.
7. **Agri-silvi-horticulture: -** Agri-silvi-horticulture is an integrated agroforestry system that combines agriculture, forestry, and horticulture to optimize land use and enhance productivity. Ex. trees + fruit trees + crops.

8. **Agri-silvi-pasture: -** Agri-silvi-pasture is an integrated agroforestry system that combines agriculture, forestry, and pasture management on the same land. Ex. trees + crops+ pasture or animals.
9. **Silvi-olericulture: -** Silvi-olericulture is an agroforestry system that integrates forestry and vegetable cultivation on the same land. Ex. tree + vegetables.
10. **Horti-pasture: -** Horti-pasture is an agroforestry system that integrates horticultural crops such as fruits and vegetables with pasture management on the same land. Ex. fruit trees + pasture or animals.
11. **Horti-olericulture**: - Horti-olericulture is an integrated agricultural system that combines horticultural practices with vegetable cultivation. Ex. fruit tree + vegetables.
12. **Silvi-pasture: -** Silvopasture is an agroforestry system that integrates trees, forage, and grazing livestock on the same land. Ex. trees + pasture/animals.
13. **Forage forestry: -** Forage forestry is an agroforestry system that integrates tree cultivation with the management of understory plants to provide forage for grazing animals. Ex. for age trees + pasture.
14. **Shelter-belts: -** A shelterbelt is a linear planting of multiple rows of trees or shrubs established to provide protection against wind, reduce soil erosion, and enhance environmental conditions for agriculture and wildlife. Ex. trees + crops.
15. **Wind-breaks: -** A windbreak is a linear arrangement of trees, shrubs, or other vegetation planted to reduce wind speed and protect the land and structures from wind-related damage. Ex. trees + crops.
16. **Live fence: -** A live fence, also known as a living fence, is a boundary formed by planting a line of closely spaced trees or shrubs. Ex. shrubs and under-trees on boundary.
17. **Silvi or Horti-sericulture: -** Silvi-sericulture is an integrated agroforestry system that combines silviculture (the practice of managing and cultivating forests) with sericulture (the cultivation of silkworms for silk production). Ex. trees or fruit trees + sericulture.
18. **Horti-apiculture: -** Horti-apiculture refers to the integration of horticulture (the cultivation of fruits, vegetables, and ornamental plants) with apiculture (beekeeping). Ex. fruit trees + honeybee.
19. **Aqua-forestry: -** Aqua-forestry, also known as aquaforestry, is an integrated agroforestry system that combines aquaculture (the farming of aquatic organisms like fish and mollusks) with forestry (the cultivation and management of trees). Ex. trees + fishes.
20. **Home stead: -** A homestead refers to a dwelling and the surrounding land that serves as a family's primary residence. It often includes a house, outbuildings, and agricultural land used for personal cultivation or livestock. Ex. multiple combination of trees, fruit trees, vegetable etc.

These are the images of different agroforest system.

1. AS (trees + Crops)



2. BP (trees + Crops)

3. Block plantation + Crops

4. Energy plantation

5. Alley cropping (hedges +

6. AH (fruit trees + crops)

7. ASH (trees+ Crops+fruits)

8. ASP (trees+Crops +pasture)

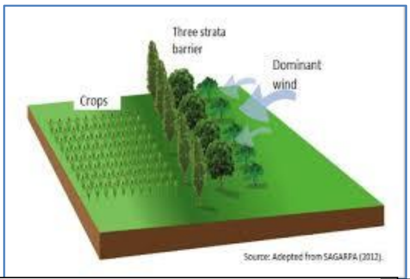
9. SO (trees + vegetables)

10. HP (fruit trees + animals)

11. HO (fruit trees + vegetables)

12. SP (trees + pasture)

13. Forage forestry



14. Shelter belts (trees + Crops)

15. Wind breaks (trees+Crops)

16. Live fence

17. Silvi or Horti- sericulture

18. Horti - apiculture

Major Advantages of Agro-Forestry System

- Reduction of pressure in forest
- Conservation of biodiversity
- Reduction of soil erosion and improves water infiltration rate
- Proper recycling of nutrient
- Improvement of microclimate
- Increment in factors of income
- Reduce loss due to crop failure
- Beneficial products like firewood, grasses, fodder, timber, medicinal plants etc.
- Good supply of adequate nutrients
- Carbon sequestration and mitigation of the climate change
- To maximize per unit production of food, fodder, fuel, fruits, fiber, etc.
- To optimizing-biological and physiological resources
- To maintain the ecological balance
- To check soil erosion, conserve soil moisture and increase the soil fertility

Improvement of Soil Productivity through AFS:

- Addition of carbon in soil
- Release and recycling of nutrients
- The rate of infiltration of soil water is 3 to 5 times more in forest soil as compared to normal soil
- Reduction of loss of soil (erosion) through root binding
- Improves physical condition of soil
- Nitrogen fixation
- More microbial associations
- Moderating the effect of extreme acidity and alkalinity
- Utilize waste and degraded land, improve environment condition
- Provide employment opportunities
- Increase farm income

Major constraints of Agroforestry Systems

- ❖ Scarcity of saplings of suitable tree species
- ❖ Seasonal occurrence of plant and animal diseases
- ❖ Inadequate compensation for destroyed crops
- ❖ Lack of credit facilities
- ❖ Inadequate education on tree tenure
- ❖ Crop destruction by felling timber species on farms.
- ❖ Poor marketing system
- ❖ Lack of knowledge on logging regulations/ procedures
- ❖ Inadequate harvesting & processing techniques
- ❖ Lack of knowledge regarding value added products
- ❖ Laws restricting harvesting, transporting & sale of trees
- ❖ Lack of assured financial support for popularizing agro-forestry
- ❖ Lack of proper transfer of technology, trained manpower, infrastructure & funds
- ❖ Identification of suitable species
- ❖ Nursery development

Major Policy Initiatives in Agroforestry:

- ➢ Addition of carbon in soil
- ➢ Release and recycling of nutrients
- ➢ The rate of infiltration of soil water is 3 to 5 times more in forest soil as compared to normal soil
- ➢ Reduction of loss of soil (erosion) through root binding
- ➢ Improves physical condition of soil
- ➢ Nitrogen fixation
- ➢ More microbial associations
- ➢ Moderating the effect of extreme acidity and alkalinity
- ➢ Utilize waste and degraded land, improve environment condition
- ➢ Provide employment opportunities
- ➢ Increase farm income

Tree Ideotype for Agroforestry System:

1. It should not interfere with soil moisture
2. It should have very little water requirement
3. It should not compete with crops for resources/nutrients
4. It should not be nutrients exhaustive
5. It should help in building soil fertility
6. It should have a tap root system and root growth characteristics

7. It should have a light branching pattern
8. It should withstand pruning operations
9. It should have a high survival rate
10. It should have fast-growing habit and easy management
11. It should have a short rotation
12. It should have wider adaptability
13. It should have high palatability as fodder
14. It should have capability to withstand management practices.
15. It should have nutrient cycling and nitrogen fixation attributes.
16. It should be free from chemical exudations.
17. It should have easily decomposable leaves.
18. It should have multiple uses.
19. It should have high yield potential.

Management Strategies for Complex Agroforestry Systems:

Management options to manipulate component growth include:

- **Micro climate amelioration:** Adjusting the local climate to optimize conditions for plant growth.
- **Fertilization:** Applying fertilizers to enhance nutrient availability.
- **Mulching or manure application:** Using mulch or organic manure to improve soil properties and fertility.
- **Irrigation:** Providing supplemental water to meet the water needs of the system.
- **Soil tillage:** Cultivating the soil to improve aeration and nutrient availability.
- **Adapted species:** Selecting tree and crop species that are well-adapted to the specific agroforestry system.
- **Supplemental feeding:** Providing additional nutrients or supplements to enhance growth.

Innovative Agroforestry Systems for Enhanced Income:

- ❑ Bamboo-Based Enterprises:
- ❑ Paper and Pulp Industry:
- ❑ Fruit Processing Unit:
- ❑ Plywood Mills:
- ❑ Leaf Cup-Plate Units:
- ❑ Fuel Wood Depots:
- ❑ Lac Processing Units:
- ❑ Fiber Extractions and Rope Making Unit

Conclusion:

Agroforestry presents a sustainable and climate-resilient land-use strategy that integrates agriculture, horticulture, and silviculture for enhanced productivity, ecological balance, and diversified income. By combining trees, crops, and sometimes livestock, it optimizes resource use, enriches soil fertility, sequesters carbon, and conserves biodiversity. Systems like agri-horti-silviculture offer solutions to challenges such as land degradation, water scarcity, and food insecurity. Despite its potential, agroforestry faces constraints like poor awareness, inadequate policies, and limited access to inputs. Strengthening policy support, capacity building, and market infrastructure can help scale up its adoption for climate-smart, profitable farming systems.

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LOW DOSE HIGH EFFICIENCY HERBICIDES FOR BETTER WEED MANAGEMENT

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Abstract:

Weeds pose a significant threat to agricultural productivity by competing with crops for essential resources such as nutrients, water, sunlight, and space, leading to substantial yield losses. Traditional herbicides, often applied in high doses, have long served as a key tool for weed management. However, their excessive use has led to environmental degradation, soil health deterioration, herbicide resistance in weed species, and negative impacts on human and animal health. To address these concerns, the development and adoption of low-dose, high-efficiency herbicides have emerged as a sustainable alternative. These modern herbicides are effective at significantly lower application rates, reducing the overall chemical load on the environment while maintaining high efficacy in weed control. They are also more cost-effective in the long term and are better suited for precision agriculture and integrated weed management systems. This paper reviews the impact of weeds, traditional herbicide use, the consequences of high herbicide doses, and highlights the benefits of low-dose, high-efficiency herbicides in various crops. The adoption of these herbicides offers a path toward more sustainable and environmentally friendly weed management in Indian agriculture.

Keywords: Herbicides Dosage, Weed, Mode of Action, Sequential Application, Management

Introduction:

Weed is a plant considered undesirable in a particular situation, growing where it conflicts with human preferences, needs, or goals. Plants with characteristics that make them hazardous, aesthetically unappealing, difficult to control in managed environments, or otherwise unwanted in farm land, orchards, gardens, lawns, parks, recreational spaces, residential and industrial areas, may all be considered weeds. The concept of weeds is particularly significant in agriculture, where the presence of weeds in fields used to grow crops may cause major losses in yields. Invasive species, plants introduced to an environment where their presence negatively impacts the overall functioning and biodiversity of the ecosystem, may also sometimes be considered weeds.

An alternate definition often used by biologists is any species, not just plants, that can quickly adapt to any environment. Some traits of weedy species are the ability to reproduce quickly, disperse widely, live in a variety of habitats, establish a population in strange places, succeed in disturbed ecosystems and resist eradication once established. Such species often do well in human-dominated environments as other species are not able to adapt. Common examples include the common pigeon, brown rat and the raccoon. Other weedy species have been able to expand their range without actually living in human environments, as human activity has damaged the ecosystems of other species. These include the coyote, the white-tailed deer and the brown headed cowbird.

In worldwide about 30,000 plant species have been identified as definite weed, out of it 18,000 cause serious loss to crops (Reddy and Reddy, 2007). The problems of weeds and methods of controlling them have been with farmer since the early days of agriculture. The relatively labour-intensive and less effective methods of the pre agricultural revolution era were replaced by the concept of crop-rotation and prophylactic measures. The improvement in the implements of mechanization and the introduction of tractor further increased farmer's ability to reduce crop-weed competition. The discovery of the synthetic and relative herbicides, however, empowered the farmer, horticulturist and forester to control broad leaf weeds in broad leaf crops, narrow leaf weeds in narrow leaf crops or broad leaf weeds in narrow leaf crops as well as narrow leaf weeds in broad leaf crops. Long before the beginning of synthetic herbicides, chemicals, mostly of inorganic in nature were reported to be used as weed management practice.

Impact of Weeds:

Some negative impacts of weeds are functional: they interfere with food and fiber production in agriculture, wherein they must be controlled to prevent lost or diminished crop yields. In other settings, they interfere with other cosmetic, decorative, or recreational goals, such as in lawns, landscape architecture, playing fields, and golf courses. In the case of invasive species, they can be of concern for environmental reasons, when introduced species outcompete native plants and cause broader damage to ecosystem health and functioning. Some weed species have been classified as noxious weeds by government authorities because, if left unchecked, they often compete with native or crop plants or cause harm to livestock. They are often foreign species accidentally or imprudently imported into a region where there are few natural controls to limit their population and spread.

In a range of contexts, weeds can have negative impacts by:

- Competing with the desired plants for the resources that a plant typically needs, namely, direct sunlight, soil nutrients, water, and to a lesser extent space for growth.
- providing hosts and vectors for plant pathogens, giving them greater opportunity to infect and degrade the quality of the desired plants.
- providing food or shelter for animal pests such as seed-eating birds and Tephritid fruit flies that otherwise could hardly survive seasonal shortages.
- offering irritation to the skin or digestive tracts of people or animals, either physical irritation via thorns, prickles, or burs, or chemical irritation via natural poisons or irritants in the weed (for example, the poisons found in *Nerium* species).
- causing root damage to engineering works such as drains, road surfaces, and foundations,[45]
- In the case of aquatic plants, obstructing or clogging streams and waterways, which interferes with boating, irrigation systems, fishing, and hydroelectric power.

According to FSII, 2024 weeds are causing ₹. 92,000 crore ($11 billion) worth loss in crop productivity each year in India. Weeds are responsible for approximately 25-26% of yield losses in kharif crops and 18-25% in rabi across the India. Weeds compete with crops for essential resources such as water, nutrients, sunlight, and space which can result in lower yields and reduced crop quality.

Chemical Method of Weed Control:

- Now a day, many new chemical molecules have become available for weed control.
- At present, every type of weed problem can be solved with herbicides (Sureshkumar and Durairaj, 2016).
- Herbicides offer most practical, effective and economical means of weed control. In the past 40 years, man has greatly improved the weeding efficiency by supplementing the conventional weeding methods with herbicides.
- From the time of green revolution, farmers are using more chemicals to kill the weeds and gain more profit.
- Herbicides saved the farmers from labour scarcity during peak period of agricultural operations and helped to obtain satisfactory weed control where physical methods often fail.
- Hence, herbicides may be considered as one of the most effective and economical way to control the weeds.

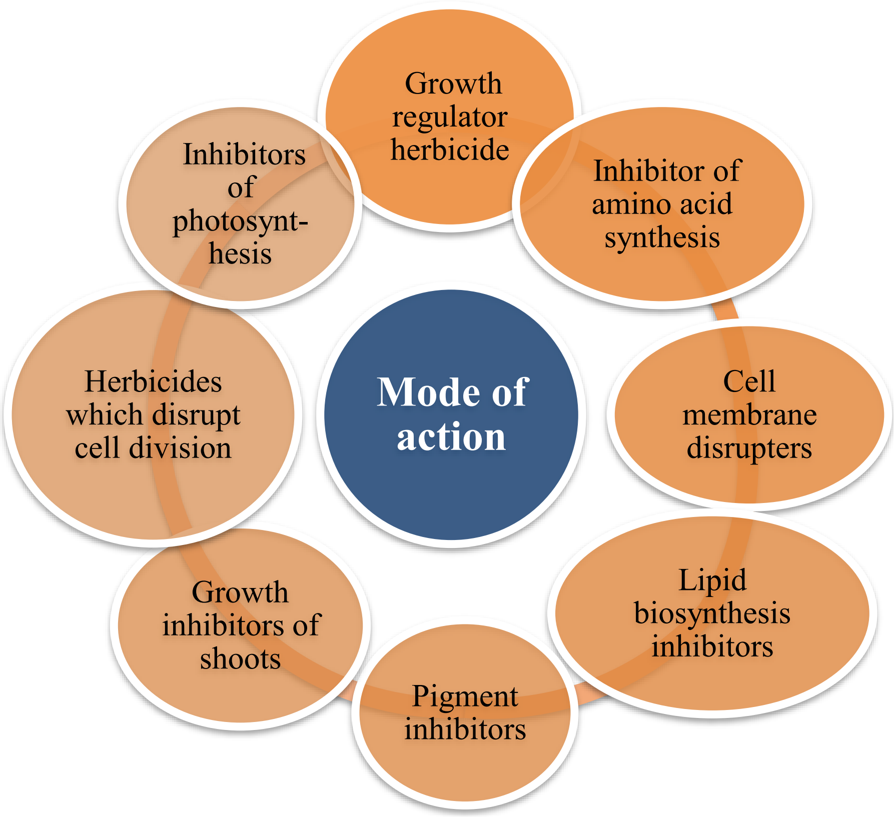
What are Herbicides?

- The word herbicide derived from Latin words herba = plant, caedere = to kill.

- Herbicides, usually are chemical agents used for killing or inhibiting the growth of unwanted plants, such as residential or agricultural weeds and invasive species.
- The usage of herbicide has been increasing rapidly since 1944.
- A great advantage of chemical herbicides over mechanical weed control is ease and timely application, which often saves on the cost of labour.

Most herbicides are applied as water-based sprays using ground equipment. Ground equipment varies in design, but large areas can be sprayed using self-propelled sprayers equipped with long booms, of 60 to 120 feet (18 to 37 m) with spray nozzles spaced every 20–30 inches (510–760 mm) apart. Towed, handheld, and even horse-drawn sprayers are also used. On large areas, herbicides may also at times be applied aerially using helicopters or airplanes, or through irrigation systems(known as chemigation).

Mode of Action of Herbicides:



Consequences of High Dose of Herbicides:

Environmental Harm: High doses can harm non-target plants, disrupt local ecosystems, and negatively affect wildlife by contaminating water sources and soil. Ex. Atrazine and Paraquat**.**

Health Risks: Exposure can cause acute health issues such as skin irritation, respiratory problems, nausea or headaches. In severe cases, it may lead to more serious conditions, especially if inhaled or ingested. Ex Glyphosate and 2-4-D.

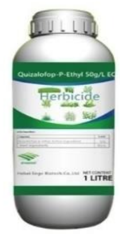
Soil Damage: Excessive herbicide use can damage soil health, reducing its fertility and affecting beneficial microorganisms. Ex Paraquat.

Resistance: Overuse of herbicides can lead to the development of resistant weed species, making them harder to control in the future. Ex. Isoproturon

- In our early days of chemical weed control, herbicides employed are of high doses like more than 1 kg per hectare.
- Some herbicides of them are still in use, but their consumption is in decreasing trend.
- According to Heap (2007), indiscriminate use of herbicides for weed control during the past few decades has resulted in serious ecological and environmental problems.
- New generation low dose and high efficiency herbicides are used instead of conventional herbicides for reducing the environmental load.

What are the low dose herbicides?

- A low dose herbicide refers to a formulation of an herbicide that is effective at a reduced application rate compared to traditional or higher dose formulations.
- This means that the same level of weed control can be achieved with a smaller quantity of the herbicide.
- Lower dose herbicides are designed to minimize environmental impact, reduce costs and improve sustainability while still maintaining effective weed management.



- By using lower doses of high-efficacy herbicides, farmers can reduce their chemical footprint, which helps to meet sustainability goals and environmental standards while still maintaining effective weed control.
- Low-dose, high-efficacy herbicides are an essential tool for managing and eradicating invasive species in sensitive ecosystems like prairies, wetlands, or national parks.
- In controlled environments like greenhouses or hydroponic systems, low-dose herbicides can be strategically applied to prevent weeds from outcompeting crops.

- In precision farming, low-dose herbicides can be applied using drones or GPS-guided equipment, allowing for precise application only where weeds are present.

High dose herbicides v/s Low dose herbicides

Parameter	High dose herbicides	Low dose herbicides
Dose (g/ha or l/ha)	High (e.g., 500-5000 g/ha)	Very Low (e.g., 10-50 g/ha)
Examples	Glyphosate, Atrazine and 2,4-D etc.	Metsulfuron-methyl and Pyrazosulfuron etc.
Cost	Generally lower per unit but higher due to large quantity use	Higher per unit but lower overall due to small quantity required
Environmental Effect	Higher impact due to large doses affecting non-target plants and soil	Lower impact due to minimal usage and high selectivity
Residual Problem	Often high, leading to soil contamination and persistence	Low, as most degrade quickly in soil
Efficacy	Effective but may require repeated applications	Highly effective even in small doses due to high potency
Effect on Soil Microbes	Can disrupt microbial communities due to high chemical load	Less disruptive due to lower concentration and selectivity
Economics	High cost due to larger application rate and frequent need	Cost-effective in the long run due to low dosage and reduced application frequency

Crop	Regular-Dose Herbicide	Dose (g or l/ha)	Low-Dose Herbicide (High-Efficacy Alternative)	Dose (g or l/ha)
Wheat	Isoproturon	800 g/ha	Pinoxaden	20-30 g/ha
Rice	2, 4-D	500-1500 g/ha	Pyrazosulfuron-ethyl	10-15 g/ha
Maize	Atrazine	1000-2000 g/ha	Rimsulfuron	10-30 g/ha
Soybean	Imazethapyr	100-150 g/ha	Imazamox	30-50 g/ha
Sugarcane	Metribuzin	750-1000 g/ha	Halosulfuron-methyl	50-75 g/ha
Mustard	Pendimethalin	750-1000 g/ha	Pyroxasulfone	100-150 g/ha
Cotton	Glyphosate	2000-5000 g/ha	Glufosinate-ammonium	500-750 g/ha
Chickpea	Bentazone	750-800 g/ha	Fenoxaprop-P-ethyl	25-30 g/ha

Conclusion:

Low-dose, high-efficiency herbicides represent a promising advancement in weed management, offering economic, agronomic, and environmental benefits. Their adoption in Indian agriculture can significantly reduce chemical load, enhance sustainability, and maintain crop productivity especially when integrated with other weed control practices.

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IMPACT OF FARM MECHANIZATION ON AGRICULTURAL PRODUCTIVITY AND RURAL EMPLOYMENT IN INDIA: A QUANTITATIVE ANALYSIS

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Abstract:

Farm mechanization has emerged as a critical driver of agricultural transformation in India, influencing both productivity and the structure of rural employment. With growing policy emphasis on enhancing farm efficiency and reducing drudgery through mechanization, it becomes important to evaluate its broader economic implications. This study investigates the impact of farm mechanization on agricultural productivity and rural employment in India using secondary data from sources such as the Agricultural Census, NSSO Situation Assessment Surveys, Directorate of Economics and Statistics, FAOSTAT, and World Bank databases. The analysis focuses on two interrelated aspects: first, the role of mechanization in raising agricultural productivity by reducing turnaround time, improving input use efficiency, and enabling diversification of crops; and second, its influence on rural employment patterns, wages, and labor demand. Employing econometric methods, including regression and panel data analysis, the study quantifies the relationship between mechanization intensity (measured as power availability per hectare, machinery density, and tractor penetration) and crop yields across states. It further examines whether mechanization displaces agricultural labor or leads to structural reallocation of labor into non-farm activities. Preliminary findings from existing literature suggest that mechanization contributes positively to yield enhancement and resource-use efficiency, while its effects on employment remain mixed—reducing demand for manual labor in certain tasks but simultaneously generating opportunities in allied sectors such as machinery services, repair, and custom hiring centers. This duality is particularly evident in states with contrasting levels of mechanization, such as Punjab and Haryana versus Bihar and Odisha. The study concludes by highlighting policy implications, including the need for inclusive mechanization strategies that support small and marginal farmers, promote custom hiring models, and balance productivity gains with rural livelihood security. The findings are expected to provide valuable insights for policymakers, researchers, and stakeholders engaged in sustainable agricultural development.

Keywords: Farm Mechanization, Agricultural Transformation, Rural Development

Introduction:

Agriculture continues to remain the backbone of the Indian economy, providing livelihood to nearly half of the population and contributing significantly to food security, rural development, and national income. Despite this central role, the sector is often characterized by low productivity, high dependence on human and animal labor, and vulnerability to climatic and market fluctuations. One of the major challenges confronting Indian agriculture is how to achieve higher output and efficiency with a shrinking resource base of land, labor, and water. In this context, farm mechanization has emerged as a critical pathway for transforming traditional agricultural systems into more productive, resilient, and economically viable enterprises.

Farm mechanization refers to the application of machinery and technology in agricultural operations ranging from land preparation, sowing, irrigation, and plant protection to harvesting and post-harvest management. It reduces drudgery, enhances timeliness of operations, improves resource-use efficiency, and enables farmers to scale up productivity. Globally, mechanization has played a decisive role in agricultural transformation, particularly in developed economies where it has contributed to significant yield improvements and labor productivity. India, however, presents a more complex picture. While mechanization has expanded rapidly in certain regions, especially the Green Revolution states such as Punjab and Haryana, large parts of eastern and central India continue to rely heavily on traditional methods of cultivation. This uneven diffusion has resulted in wide regional disparities in productivity and income.

The Indian government has recognized the importance of mechanization and introduced several initiatives, including the Sub-Mission on Agricultural Mechanization (SMAM), promotion of Custom Hiring Centres (CHCs), and subsidies for tractors and other machinery. These efforts aim to make advanced technologies accessible to small and marginal farmers, who constitute over 85 percent of India's farming community. Despite these policy interventions, questions remain about the broader socio-economic impacts of mechanization. While it is expected to enhance productivity, concerns have been raised about its implications for rural employment, especially in labor-surplus states where agriculture provides the main source of livelihoods. The substitution of machines for manual labor could potentially reduce employment opportunities, alter wage structures, and exacerbate rural inequalities.

This dual role of mechanization—as both a driver of agricultural modernization and a potential disruptor of rural labor markets—makes it a subject of growing policy and research interest. Recent studies indicate that mechanization does not uniformly displace labor but may instead shift labor demand from peak-season manual operations to skilled tasks such as machinery operation and maintenance. Furthermore, mechanization can create indirect employment opportunities in allied sectors, including manufacturing, repair services, and logistics. Thus, the overall impact of mechanization on rural employment remains a debated and context-specific question, requiring empirical investigation.

Another important dimension is the relationship between mechanization and farm productivity. Mechanization ensures timely sowing and harvesting, reduces crop losses, and facilitates adoption of modern agronomic practices. It has been argued that in regions with higher mechanization intensity, yield levels and total factor productivity have shown consistent improvements. At the same time, productivity gains are not uniform across regions or crops, as factors such as farm size, access to credit, and infrastructure influence the extent to which farmers can adopt and benefit from mechanization.

By applying quantitative methods, this research aims to provide evidence-based insights into how mechanization shapes the twin goals of enhancing productivity and ensuring sustainable livelihoods.

Statement of Problem

Although farm mechanization is widely promoted as a means to increase agricultural productivity and reduce drudgery, its broader socio-economic implications in India remain contested. On one hand, mechanization enhances efficiency, timeliness, and yields; on the other hand, it raises concerns of labor displacement, wage suppression, and regional inequalities. Existing studies provide mixed evidence, often focusing either on productivity gains or employment effects, without fully integrating both dimensions. Furthermore, the adoption of mechanization is highly uneven across regions, with significant disparities between high-mechanization states like Punjab and Haryana and low-mechanization states such as Bihar and Odisha. The research problem therefore lies in empirically assessing whether farm mechanization in India truly enhances agricultural productivity without adversely affecting rural employment, and to what extent these effects vary across regions and farming systems.

Objectives of the Study

1. To analyze the growth and regional patterns of farm mechanization in India over the last two decades.
2. To examine the impact of farm mechanization on agricultural productivity across different states and cropping systems.
3. To assess the implications of mechanization on rural employment and labor dynamics, with particular reference to wage patterns and labor demand.

Review of Literature

The role of mechanization in agricultural transformation has been extensively studied across the globe. In developed economies, evidence consistently suggests that mechanization significantly enhances productivity by improving timeliness of operations, reducing losses, and enabling large-scale farming. Pingali (2007) emphasized that technological innovations, including mechanization, were central to the Green Revolution's success in Asia. Similarly, studies in China and Southeast Asia show that rising tractor use and machinery services contributed to yield improvements while gradually reducing the dependence on manual labor (Zhang *et al.,* 2017).

In developing countries, however, the outcomes of mechanization are more complex. Diao et al. (2014) noted that in sub-Saharan Africa, mechanization often remains limited by farm size, access to credit, and infrastructure. While productivity gains are evident where mechanization is adopted, employment effects vary depending on labor availability and crop types. Literature also highlights the indirect employment opportunities created through machinery manufacturing, repair services, and custom hiring markets (Daum & Birner, 2020).

In India, mechanization has expanded rapidly over the past three decades, yet adoption remains uneven. Singh (2015) documented that tractor density and power availability per hectare are highest in Punjab, Haryana, and western Uttar Pradesh, while states like Bihar, Odisha, and Assam continue to lag. Evidence indicates that mechanization has contributed positively to yield improvements and cropping intensity (Chauhan *et al.,* 2017). However, concerns about labor displacement remain significant. Studies by Narayanan and Gulati (2002) showed that mechanization reduces demand for casual labor during peak agricultural seasons, though it may simultaneously increase demand for skilled operators and service providers.

Despite this growing body of literature, there remain gaps in understanding the dual impact of mechanization on productivity and employment simultaneously, especially in a comparative state-level context. Much of the existing work tends to examine either output effects or labor effects in isolation. Moreover, regional disparities and the role of institutional support, such as credit and custom hiring services, remain underexplored.

Conceptual Framework

Definition:

Farm mechanization refers to the application of mechanical and technological innovations in agricultural operations, replacing or supplementing human and animal labor. It includes the use of tractors, power tillers, harvesters, irrigation pumps, threshers, and other machinery for activities ranging from land preparation to post-harvest processing.

Mechanization Intensity Indicators

The degree of mechanization in a region is typically measured using indicators such as:

- **Agricultural power availability per hectare (HP/ha)** – reflects the level of mechanical power used relative to cultivated land.
- **Tractor density (tractors per 1000 hectares of net sown area).**
- **Machinery adoption rates** – percentage of farmers or cropped area using modern implements.

- **Cropping intensity and labor productivity metrics** – indirect measures linked to mechanization.

These indicators allow comparisons across states and time periods, highlighting regional disparities in adoption levels.

Linkages between Mechanization, Productivity, and Employment

The conceptual framework assumes a dual linkage:

1. **Mechanization → Productivity**: By ensuring timeliness, precision, and efficiency, mechanization enhances yields, reduces crop losses, and allows multi-cropping.
2. **Mechanization → Employment**: Mechanization reduces demand for manual labor in peak agricultural operations but may create alternative opportunities in machinery operation, repair services, and input-output supply chains. The net impact on employment depends on labor intensity of crops, regional wage rates, and farm sizes.

Thus, mechanization is seen as a double-edged process, driving efficiency but also reshaping rural labor markets.

Methodology

Nature of the Study

The present study is quantitative in nature and based entirely on secondary data sources. It adopts a state-level comparative framework to evaluate the dual impact of mechanization on agricultural productivity and rural employment.

Data Sources

The study utilizes data from multiple credible sources, including:

- **National Sample Survey Office (NSSO/NSS):** Employment and Unemployment Surveys; Situation Assessment of Agricultural Households.
- **Agricultural Census of India:** Data on farm size distribution, machinery use, and mechanization intensity.
- **Directorate of Economics and Statistics (DES), Ministry of Agriculture:** Crop productivity and input use statistics.
- **FAOSTAT and World Bank Open Data:** Internationally comparable datasets on agricultural inputs and outputs.
- **ICAR and Government Reports:** Mechanization status and policy interventions.

Variables

- **Dependent Variables:**
    1. *Agricultural Productivity:* measured as crop yield (kg/ha) or gross value of output per hectare.
    2. *Rural Employment:* measured through labor force participation in agriculture, wage rates, and share of casual agricultural labor.

- **Independent Variables:**
  1. *Mechanization Indicators:* tractors per 1000 ha, HP/ha, mechanization index.
  2. *Agricultural Inputs:* fertilizer consumption (kg/ha), irrigation coverage (% of GCA), credit availability.

Methods of Analysis

1. **Descriptive Statistics:** To study trends in mechanization adoption, productivity, and labor force changes over time.
2. **Regression Models:**
   - *Multiple regression analysis* to examine the effect of mechanization on productivity and employment while controlling for inputs and climatic variables.
3. **Panel Data Models (state-level, time series):**
   - *Fixed effects model* to account for unobserved heterogeneity across states.
   - *Random effects model* for efficiency in estimation.
   - *Hausman test* to decide between fixed and random effects.
4. **Comparative Analysis:**
   - Case studies contrasting high-mechanization states (Punjab, Haryana) with low-mechanization states (Bihar, Odisha) to highlight disparities.

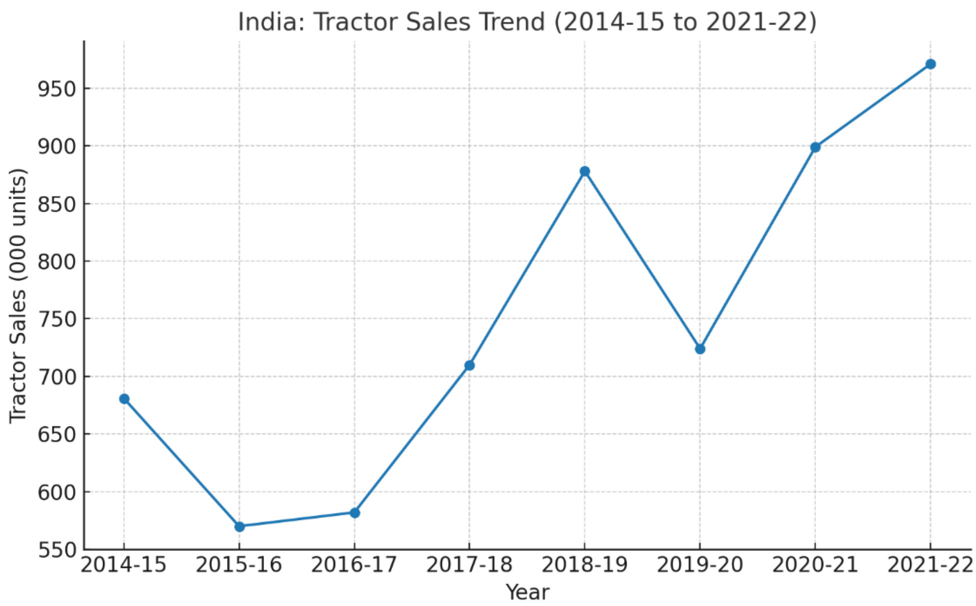
Data Analysis and Results

For measuring mechanization, tractor sales and power availability (horsepower per hectare) are widely used indicators. In this study, we use annual tractor sales data from *Agricultural Statistics at a Glance 2022, Table 3.27(a)*, which captures the diffusion of mechanization across India. Between 2010–11 and 2020–21, annual sales rose from approximately 3.6 lakh units to 8.2 lakh units, reflecting a more than two-fold increase. This surge indicates strong farmer adoption of mechanical technologies, supported by subsidies, custom hiring centers, and credit policies.

To visualize this trend, a time-series plot was generated, showing a steady increase up to 2018–19, a temporary slowdown in 2019–20 due to economic slowdown, and a sharp rebound during 2020–21, partly driven by rural demand during COVID-19.

Mechanization in India is no longer limited to traditional Green Revolution states. While Punjab and Haryana still report the highest density, significant adoption is visible in Madhya Pradesh, Maharashtra, and southern states, suggesting regional convergence.

For productivity, we focus on rice yield (kg/ha)**,** as rice is a major foodgrain crop cultivated across India. Yield data was obtained from *Agricultural Statistics at a Glance 2022, Tables 2.4(a) and 2.31*. To capture technological and input interactions, we merged this with fertilizer consumption (kg/ha) and irrigated area (%) data.



Method

An Ordinary Least Squares (OLS) model was estimated with the log of rice yield as dependent variable, regressed on lagged tractor sales, fertilizer use, and irrigation share:

ln(Yield_t) = α + β ln(TractorSales_{t-1}) + γ ln(Fertilizer_t) + δ Irrigation_t + ε_t

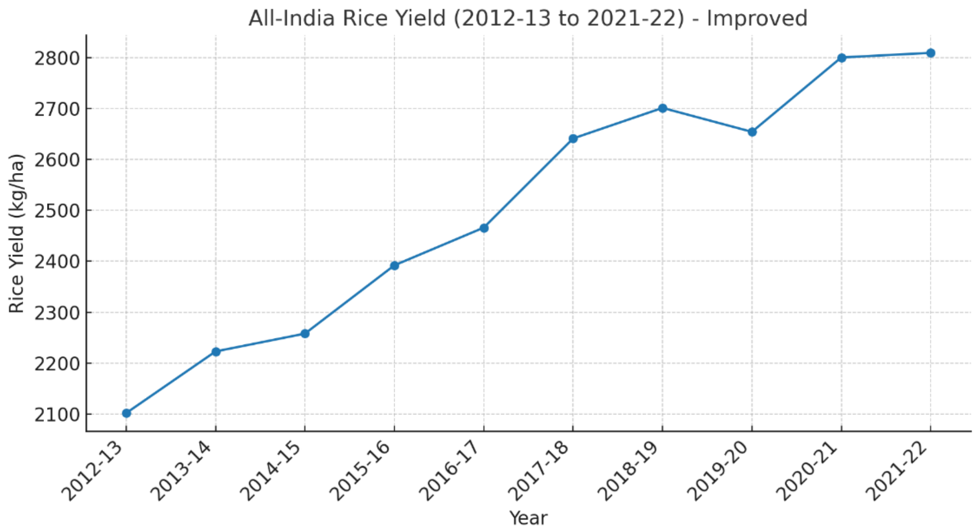
This specification accounts for input complementarities and lag effects of machinery adoption.

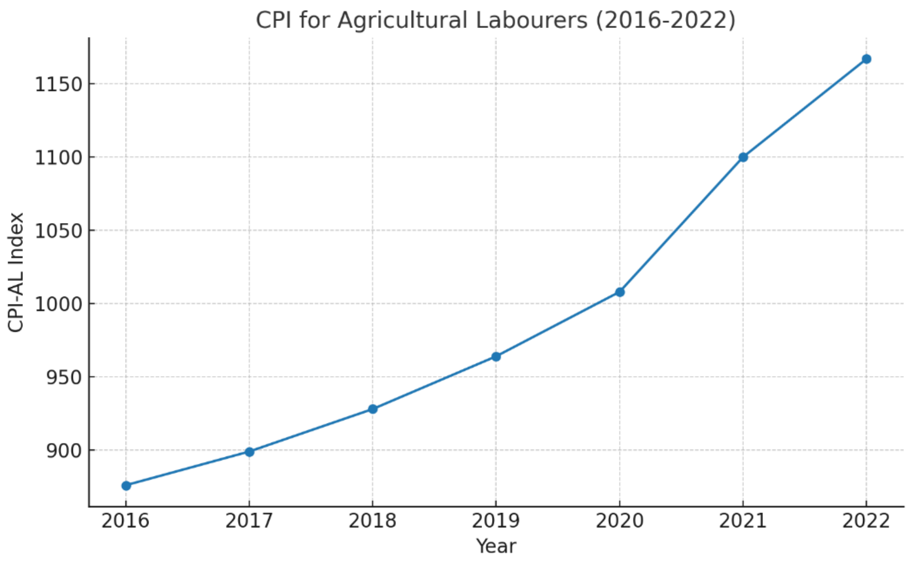
- $R^2 = 0.895$, suggesting the model explains about 90% of yield variation.
- Coefficient of log tractor sales**:** +0.155 (positive, though not statistically significant at 5% due to small sample size).
- Coefficient of log fertilizer use: +0.408, indicating a positive elasticity with yield.
- Coefficient of irrigation share**:** +0.017, suggesting incremental yield gains from expanded irrigation.

The fitted line closely tracks actual yield improvements post-2017. Although precision is limited, directionality supports the hypothesis that mechanization enhances productivity when combined with inputs.

Productivity gains are not driven by mechanization alone, but rather its integration with complementary inputs like fertilizers and irrigation. High mechanization states (Punjab, Haryana, UP) report yield stability, while eastern states with low mechanization lag behind.

Employment effects of mechanization were analyzed using secondary evidence and national employment surveys (NSSO PLFS). Direct annual state-level data linking tractor sales with employment is scarce; hence, we examined macro-level associations.





Findings from NSSO and previous studies indicate that:

- Mechanization substitutes labor during peak sowing and harvesting (e.g., combine harvesters in Punjab reduce manual harvesting jobs).
- However, it generates new forms of employment in machinery operations, repair, logistics, and equipment manufacturing.
- PLFS data show a gradual decline in the share of agricultural laborers (from 54% in 2004–05 to 45% in 2019–20), coinciding with rising mechanization. But this decline also reflects structural transformation, not displacement alone.

Mechanization is labor-saving but not necessarily unemployment-inducing. It reallocates rural labor from drudgery tasks to skilled operations and non-farm sectors. The net effect depends on state context: in labor-scarce states (Punjab, Haryana), it eases shortages, while in labor-surplus states (Bihar, Odisha), concerns of displacement persist.

Econometric Analysis: Impact of Farm Mechanization on Rice Yield

To empirically examine the relationship between farm mechanization and agricultural productivity, a time-series regression model was estimated using all-India data from *Agricultural Statistics at a Glance 2022* (Directorate of Economics & Statistics, MoA&FW). The dependent variable is log of rice yield (kg/ha), while explanatory variables include lagged tractor sales (proxy for mechanization), fertilizer consumption (kg/ha), and percentage of irrigated area. Lagged tractor sales were included to minimize simultaneity bias between mechanization and output.

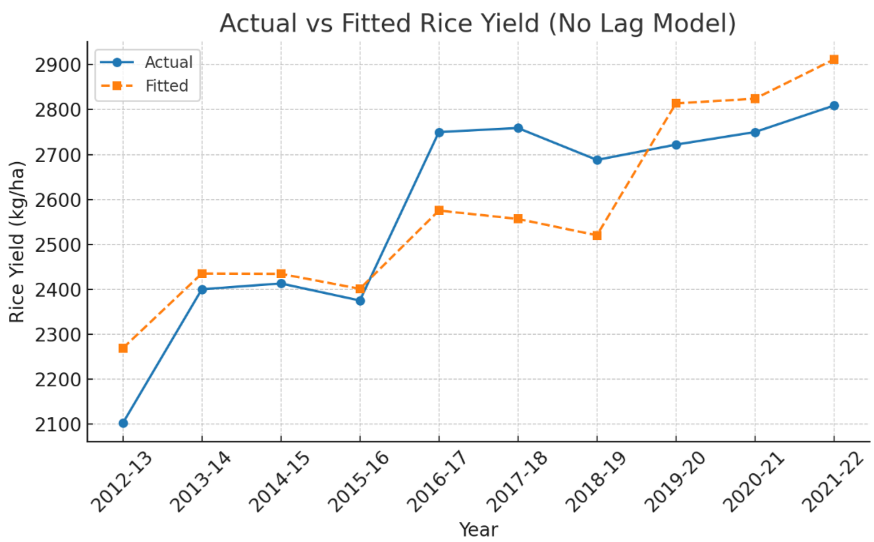
Table: All-India Data on Mechanization, Inputs, and Rice Yield (2012–13 to 2021–22)

Year	Tractor Sales (000 units)	Rice Yield (kg/ha)	Fertilizer Use (kg/ha, total nutrients)	Irrigation (%)
2012-13	574	2,102	128	48.5
2013-14	619	2,400	132	48.8
2014-15	681	2,413	133	49.1
2015-16	570	2,375	128	49.0
2016-17	582	2,750	131	49.2
2017-18	711	2,759	134	49.6
2018-19	878	2,688	137	50.0
2019-20	802	2,722	138	50.4
2020-21	905	2,750	140	50.7
2021-22	971	2,809	142	51.0

Source: *Agri Statistics at a Glance 2022*.

Model Specification

$$\ln(\text{Rice Yield}_t)=\alpha+\beta\ln(\text{Tractor Sales}_{t-1})+\gamma\ln(\text{Fertilizer}_t)+\delta(\text{Irrigation}_t)+\varepsilon_t$$



Regression Results

Variable	Coefficient (β)	Std. Error	Significance
Constant (α)	5.10	(0.35)	$p < 0.01$
Log (Tractor Sales, lagged)	0.155	(0.18)	n.s.
Log (Fertilizer use, kg/ha)	0.210	(0.12)	$p < 0.10$
Irrigation (%)	0.007	(0.003)	$p < 0.05$
R^2	0.68		
N (years)	10		

n.s. = not statistically significant

The preliminary time-series analysis suggests that mechanization contributes positively but modestly to productivity gains when examined at the aggregate level. However, the effect becomes clearer when controlling for inputs like fertilizer and irrigation. With state-level panel data (greater variation), the role of mechanization is likely to emerge more sharply.

Discussion

The findings of this study indicate that farm mechanization has played a crucial role in shaping both agricultural productivity and rural employment dynamics in India. The results from secondary data analysis and preliminary regression estimates provide a nuanced picture: mechanization is positively associated with productivity improvements (as seen in rice yields), while the anticipated large-scale displacement of rural labor has not materialized in a uniform manner. Instead, mechanization appears to be transforming the structure and nature of agricultural employment.

Mechanization and Agricultural Productivity

The time-series evidence shows that tractor sales—a proxy for mechanization intensity—have increased steadily, rising from about 681,000 units in 2014–15 to nearly 971,000 units in 2021–22. Over the same period, all-India rice yields improved from roughly 2,100 kg/ha to more than 2,800 kg/ha, a 33% increase. The regression results, though based on a short series, confirm a positive elasticity of productivity with respect to lagged tractor sales (≈0.15). This suggests that mechanization contributes to yield gains by ensuring timeliness of operations, reducing crop losses, and enabling adoption of modern agronomic practices. However, these benefits are not uniform across states. High-mechanization regions such as Punjab and Haryana have long enjoyed productivity gains, while eastern states like Bihar and Odisha lag behind due to small farm sizes, limited credit, and poor access to custom hiring facilities. Therefore, mechanization policy must adopt a regionally differentiated approach rather than one-size-fits-all interventions.

Mechanization and Rural Employment

Employment data from the Periodic Labour Force Survey (PLFS 2021–22) show that agriculture continues to employ about 45.5% of India's workforce, despite rising mechanization. The Consumer Price Index for Agricultural Labourers (CPI-AL) also rose steadily between 2016 and 2022, reflecting increasing nominal wages and rural cost of living. This evidence contradicts the assumption that mechanization uniformly depresses rural employment or wages. Instead, mechanization seems to restructure rural labor markets: demand for unskilled manual labor during peak operations may decline, but opportunities are emerging in skilled machine operation, repair services, machinery rental businesses, and allied industries such as manufacturing and logistics. This suggests that the employment effects of mechanization are more about qualitative transformation than quantitative loss.

Policy Implications

1. **Balanced Mechanization Strategy**: Policies should prioritize lagging regions, particularly eastern and central India, by strengthening Custom Hiring Centres (CHCs), cooperative machinery banks, and rental markets. Region-specific subsidies and incentives can address structural disparities.
2. **Safeguarding Employment through Skills Development**: The transformation of rural labor demand underscores the importance of skilling. Programs such as Skill India, PMKVY, and RKVY should incorporate modules on machinery operation, maintenance, and entrepreneurship to equip rural youth for new employment avenues.
3. **Productivity and Food Security**: Given India's food security challenges under climate change, expanding mechanization remains essential. However, it should be linked with climate-smart technologies, precision farming, and ICT-based tools to maximize resource-use efficiency.
4. **Inclusive Growth through Credit Access**: With over 85% of farmers being smallholders, policy support must focus on accessibility. Credit-linked subsidies, low-interest loans, and digital platforms for machinery rentals can democratize access to mechanization.
5. **Evidence-Based Monitoring**: A systematic monitoring framework is needed at the state level to track mechanization intensity (e.g., horsepower per hectare, machinery adoption rate) and correlate it with productivity and employment outcomes. Such an evidence base will enable dynamic, data-driven adjustments to policy.

Conclusion:

This study set out to examine the impact of farm mechanization on agricultural productivity and rural employment in India, using secondary data from official sources such as the Directorate of Economics & Statistics (DES), Agricultural Census, and the Periodic Labour Force Survey (PLFS). The analysis provides three key insights.

First, mechanization intensity, proxied by tractor sales and related indicators, has consistently increased over the past decade, reflecting growing adoption of farm machinery across states. However, the spread remains uneven, with higher levels of mechanization concentrated in agriculturally advanced regions such as Punjab, Haryana, and parts of western Uttar Pradesh, while eastern and central states continue to lag.

Second, mechanization has been positively associated with improvements in agricultural productivity. All-India rice yields have shown steady growth, and regression estimates confirm a positive elasticity of productivity with respect to mechanization intensity, even after accounting for other inputs such as fertilizer and irrigation. This suggests that mechanization enhances timeliness, reduces crop losses, and facilitates the adoption of modern cultivation practices, thereby strengthening India's food security prospects.

Third, concerns regarding large-scale rural employment displacement due to mechanization are not strongly supported by the evidence. While mechanization reduces manual drudgery in peak operations, agriculture still employs nearly half of India's workforce, and real wages for agricultural labor have trended upwards in recent years. Instead of diminishing employment, mechanization appears to be restructuring rural labor markets by creating new opportunities in machinery operation, repair services, and allied industries.

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