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# Advances in Agriculture, Horticulture and Animal Husbandry

## Volume III


Editors:

Dr. Archana Suyal

Mr. C. P. Bhagat

Dr. Dinesh D. Wanule

Mr. Sandeep Kumar



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## Editors

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|---|---|
| **Dr. Archana Suyal**<br>Department of R&D,<br>Patanjali Natural Coloroma,<br>Patanjali Group, Haridwar | **Mr. C. P. Bhagat**<br>Department of Botany,<br>Karmaveer Hire College,<br>Gargoti, Dist. Kolhapur, M.S. |
| **Dr. Dinesh D. Wanule**<br>Department of Zoology,<br>B. K. Birla College (Autonomous),<br>Kalyan, M.S. | **Mr. Sandeep Kumar**<br>Sri Karan Narendra Agriculture University,<br>Jobner,<br>Rajasthan |

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**E-mail: bhumipublishing@gmail.com**

# *PREFACE*

*Agriculture, horticulture, and animal husbandry are the cornerstones of human sustenance and economic development. Over the years, these fields have witnessed remarkable transformations driven by innovations in science, technology, and management practices. The escalating demand for food, nutritional security, and sustainable production systems has created an urgent need to explore novel strategies, refine traditional practices, and integrate modern technologies for higher productivity and efficiency. This book, Advances in Agriculture, Horticulture and Animal Husbandry, brings together contemporary research, practical insights, and emerging trends that are reshaping these interrelated disciplines.*

*The chapters in this volume cover a broad spectrum of topics, ranging from crop improvement, precision farming, soil and water management, pest and disease control, to advanced horticultural practices and innovations in livestock management. The book emphasizes sustainable approaches, highlighting organic farming, integrated pest management, climate-resilient crop production, and improved feeding and breeding strategies in animal husbandry. By combining theoretical knowledge with applied research, it offers a holistic perspective that is relevant to academicians, researchers, policymakers, and practitioners alike.*

*Special attention has been given to the role of technology and digital tools in modern agriculture, including mechanization, remote sensing, smart irrigation, and data-driven decision-making in crop and livestock management. The integration of biotechnology, molecular breeding, and novel horticultural techniques demonstrates the potential to enhance productivity while conserving natural resources. Similarly, advancements in animal health, nutrition, and genetic improvement underscore the critical contribution of animal husbandry to global food security and rural livelihoods.*

*We hope this book serves as a valuable reference for students, researchers, and professionals seeking to understand the current trends, challenges, and opportunities in agriculture, horticulture, and animal husbandry. It is our sincere hope that the knowledge shared in this volume will inspire further research, promote innovation, and support sustainable practices that ensure food security, environmental protection, and socio-economic development.*

**- Editors**

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# ANTIMICROBIAL RESISTANCE IN PLANT PATHOLOGY: A GROWING CONCERN

**Varala Krishnaveni*[1], Sathish Kota[2] and Rama Krishna V[3]**
[1]Department of Plant Pathology,
Vasantrao Naik Marathwada Krishi Vidyapeeth University, Parbhani, Maharastra, 431402
[2]Department of Agricultural Entomology,
Indira Gandhi Krishi Vishwavidyalaya (IGKV), Raipur, Chhattisgarh 492012
[2]Department of Agricultural Extension Education, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana 500030
*Corresponding author E-mail: varalakrishnaveni4444@gmail.com

**Abstract:**

Antimicrobial resistance (AMR) has emerged as a pressing challenge in plant pathology, threatening the sustainability of Agriculture and global food security. Excessive and inappropriate use of antimicrobial chemicals in agriculture has accelerated the evolution of resistant strains of fungi, bacteria, and other plant pathogens. This resistance undermines conventional disease management practices and contributes to economic losses, reduced crop productivity, and compromised food quality. The mechanisms of resistance, including target modification, efflux pump activity, enzymatic degradation, and biofilm formation, allow pathogens to withstand chemical treatments. The consequences extend beyond farm fields, influencing global agricultural trade and posing indirect risks to human and animal health through the food chain. Mitigation strategies emphasize integrated pest management (IPM), resistance management approaches, biological alternatives, and continuous monitoring and surveillance. Recent advances in nanotechnology, plant-derived antimicrobials, novel fungicides, and regulatory bans on high-risk chemicals demonstrate promise in curbing AMR. Coordinated efforts involving research, policy regulation, and farmer education are essential. This chapter reviews the mechanisms, consequences, strategies, and future directions of AMR in plant pathology, highlighting the urgent need for global collaboration to preserve effective disease management practices.

**Keywords:** Antimicrobial Resistance, Biological Control, Food Security, Fungicides, Integrated Pest Management, Plant Pathology.

## Introduction:

Plant diseases caused by fungi, bacteria, and viruses account substantial losses in global agriculture every year. To combat these threats, farmers and researchers have long relied on antimicrobial chemicals, including fungicides, bactericides, and antibiotics. However, over the past few years, the indiscriminate use of these chemicals has given rise to antimicrobial resistance (AMR), where plant pathogens evolve the ability to survive chemical treatments that were once effective (McManus *et al.,* 2002).

AMR in plant pathogens has been reported across major crops such as wheat, rice, citrus, and vegetables, with resistant strains of *Alternaria*, *Fusarium*, *Xanthomonas*, and *Pseudomonas* increasingly documented (Ishii and Hollomon, 2015). This issue not only reduces the efficiency of existing plant protection chemicals but also raises concerns about food security, environmental safety, and the sustainability of agricultural practices. Sharma *et al.* (2017) reported that if left unchecked, AMR could significantly impact global food supplies, with projected agricultural losses exceeding billions of dollars annually.

**Mechanisms of Antimicrobial Resistance**

Plant pathogens employ several mechanisms to survive against antimicrobial chemicals. Those are;

1. **Target modification** – Resistant pathogens alter the binding site of the antimicrobial compound, reducing its efficacy. For example, resistance to sterol demethylation inhibitor (DMI) fungicides in *Mycosphaerella graminicola* occurs through mutations in the CYP51 gene (Cools and Fraaije, 2013).
2. **Efflux pumps** – Certain fungi and bacteria develop membrane transport systems that actively expel antimicrobial compounds from their cells, thereby reducing intracellular concentrations (Nakaune *et al.,* 1998). Ex: *Botrytis cinerea* against Multiple fungicides
3. **Enzymatic degradation** – Pathogens produce enzymes capable of breaking down or inactivating antimicrobial molecules. For instance, some bacterial plant pathogens can degrade streptomycin, rendering treatments ineffective (McManus *et al.,* 2002). Ex: *Xanthomonas* spp. inactivates antibiotic Streptomycin.
4. **Biofilm formation** – Many bacterial pathogens form biofilms on plant surfaces, creating a protective matrix that shields cells from antimicrobial penetration. Biofilms also promote horizontal gene transfer, further accelerating resistance (Sharma and Singh, 2016). Ex: *Pseudomonas syringae* shows Reduced antimicrobial penetration due to Biofilm formation.

**Consequences of Antimicrobial Resistance**

The impacts of AMR in plant pathology extend far beyond immediate crop losses.

1. **Reduced disease control** – Resistant pathogens can overcome antimicrobial chemicals, leading to frequent outbreaks and higher disease incidence (Sharma, 2015).
2. **Economic losses** – Farmers must invest in alternative or higher doses of chemicals, increasing production costs. A recent estimate suggested that AMR could cause agricultural production losses of up to $1.4 billion globally by 2050 (Science Daily, 2022).

3. **Food security threats** – Crop yield reductions and compromised food quality threaten global food availability, particularly in agriculture dependent nations (The Guardian, 2022).
4. **Environmental consequences** – Increased use of chemicals in response to resistance can disrupt ecological balance, harming beneficial microbes and increasing environmental pollution (Sharma *et al.,* 2017).

**Strategies for Mitigating Antimicrobial Resistance**

Addressing AMR requires a sustainable, comprehensive and integrated approach.

1. **Integrated Pest Management (IPM)**: IPM combines biological, cultural, physical, and chemical methods to minimize dependence on antimicrobials. Crop rotation, rouging, resistant varieties, and biological control agents such as *Trichoderma* spp. are key components (Cook, 2014).
2. **Resistance management strategies**: Rotating fungicides with different modes of action, using mixture formulations, and applying chemicals only, when necessary, can delay resistance development (FRAC, 2021).
3. **Alternative control methods**: Biological control agents (e.g., *Trichoderma, Pseudomonas*), plant-derived compounds, and nanotechnology-based formulations provide promising alternatives. Recent research into chitosan nanoparticles has shown enhanced antifungal activity with reduced chemical use (Kumar *et al.,* 2020).
4. **Monitoring and surveillance**: Systematic monitoring of resistance patterns in pathogen populations enables early detection and targeted responses (Ishii and Hollomon, 2015).

**Recent Advances, Case Studies, and Regulatory Actions**

Recent scientific breakthroughs provide hope for managing AMR in plant pathology. A new group of antifungal compounds has shown promising results against resistant fungal pathogens (Fisher *et al.,* 2022). Similarly, advances in nanotechnology allow targeted delivery of antimicrobial agents, improving efficacy while minimizing environmental impacts (Kumar *et al.,* 2020).

Case studies reveal growing concern over field-level resistance. For example, widespread resistance to QoI fungicides (*Strobilurins*) in *Botrytis cinerea* has been documented in vineyards, challenging grape disease management strategies (Fernández-Ortuno *et al.,* 2015).

**Regulatory Actions: Recently Banned Chemicals**

To combat AMR and safeguard human and environmental health, several antimicrobial agents previously used in agriculture have been banned in India:

1. **Streptomycin and Tetracycline (2024)** – Prohibited in agriculture due to their classification as critically important antimicrobials for human medicine. Their use contributed to AMR in bacterial plant pathogens (AgroPages, 2024).

2. **Monocrotophos (2023)** – An organophosphate insecticide banned in vegetable cultivation due to toxicity and associated resistance issues (Earth Journalism, 2023).
3. **Dicofol, Dinocap, Methomyl (2023)** – These hazardous pesticides were banned due to toxicity concerns and their role in environmental contamination and resistance (PAN India, 2023).
4. **Captafol (2023)** – A fungicide prohibited for foliar use and domestic manufacture because of environmental and health risks, including its contribution to resistant pathogen strains (PPQS, 2023).

These regulatory actions highlight the importance of policy interventions in AMR mitigation. By restricting high-risk chemicals, authorities aim to reduce selective pressure on pathogens, preserve the efficacy of remaining antimicrobials, and promote safer agricultural practices.

**Future Directions**

Looking ahead, a multi-pronged approach is essential for combating AMR in plant pathology:

1. **Research and development** – Investment in novel antimicrobials, nanotechnology, and biological control agents.
2. **Policy and regulation** – Strict regulations governing antimicrobial use in agriculture to ensure responsible application.
3. **Education and outreach** – Training farmers and stakeholders in AMR awareness and sustainable disease management practices (Sharma *et al.,* 2017).
4. **Global collaboration** – Sharing resistance data across countries and institutions to track emerging threats.

**Conclusion:**

Antimicrobial resistance represents one of the greatest challenges to sustainable plant disease management in the 21st century. It undermines existing agricultural practices, threatens food security, and imposes severe economic costs. However, through integrated management strategies, alternative control approaches, regulatory bans, and robust policy frameworks, the impact of AMR can be mitigated. Research, education, and international cooperation will be crucial in preserving the effectiveness of antimicrobials and ensuring resilient food production systems for the future.

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# HERBAL THERAPY AN ALTERNATE REMEDY FOR DIABETES MELLITUS IN VETERINARY PRACTICE

**T V Chaitanya Kumar*, K Padmaja and Renuka Naidu**

Department of Veterinary Biochemistry, College of Veterinary Science,

Sri Venkateswara Veterinary University, Tirupati, Andhraprasdesh-517502

*Corresponding author E-mail: meechaitanya@yahoo.co.in

Diabetes mellitus (DM) is a chronic metabolic disorder characterized by persistent hyperglycemia resulting from defects in insulin secretion, insulin action, or both. The major clinical manifestations include polyuria, glycosuria, polydipsia, polyphagia, and in severe cases, ketoacidosis. At the metabolic level, lack of insulin disrupts carbohydrate, fat, and protein metabolism, leading to long-term complications. These include microvascular complications such as retinopathy, nephropathy, and neuropathy, and macrovascular complications like coronary artery disease, peripheral vascular disease, and cerebrovascular disease (Divi *et al.,* 2012).

Globally, DM has emerged as a major epidemic, affecting approximately 463 million adults and is projected to rise to 578 million by 2030 and 700 million by 2045 (IDF, 2019).

**Type I Diabetes Mellitus**

Type I DM (Insulin Dependent Diabetes Mellitus, IDDM) is an autoimmune disorder in which pancreatic β-cells are destroyed by islet cell or insulin autoantibodies, resulting in absolute insulin deficiency. These patients invariably require insulin therapy for survival (Paschou *et al.,* 2017).

**Type II Diabetes Mellitus**

Type II DM (Non-Insulin Dependent Diabetes Mellitus, NIDDM) is the most prevalent form of diabetes, primarily resulting from insulin resistance in target tissues. Risk factors include older age, obesity, physical inactivity, and family history of diabetes (Guyton and Hall, 2006).

**Gestational Diabetes Mellitus**

Gestational diabetes mellitus (GDM) is defined as glucose intolerance with onset or first recognition during pregnancy. It affects 2–5% of pregnancies and usually resolves after delivery, though affected women are at increased risk for developing type II DM later in life (Kelly, 2014).

**Other Specific Types**

Other forms of diabetes include those caused by genetic defects of β-cell function or insulin action, diseases of the exocrine pancreas, endocrinopathies (e.g., acromegaly), and diabetes secondary to drugs, chemicals, or infections (Baynest, 2015).

**Diabetes Mellitus in Animals**

DM is common in companion animals, particularly cats and dogs, and to a lesser extent in cattle, horses, sheep, pigs, and birds. Risk factors include genetics, age, obesity, and environmental influences (Kaoud, 2017).

- Dogs: Usually develop type I DM like human type I. Breeds such as Samoyed, Australian Terrier, Keeshond, and Cairn Terrier are predisposed (Nelson and Reusch, 2014).
- Cats: Most frequently develop type II DM, with prevalence between 0.25–1%. Obesity increases the risk two-fold in cats and four-fold in dogs (Laflamme, 2012; Gottlieb and Rand, 2018). Pathology is like human type II DM, with islet amyloid deposition, β-cell dysfunction, and secondary retinal and neural complications (Niaz *et al.,* 2018).
- Birds: Diabetes is associated with glucagon overproduction.

**Present Status of Drugs in Diabetes Mellitus Treatment**

Current pharmacological therapies include oral hypoglycemic agents (biguanides, thiazolidinediones, sulfonylureas) and injectable insulin. These agents either increase insulin secretion or improve insulin sensitivity, but have drawbacks including side effects, limited efficacy, and the need for lifelong use (Kumari *et al.,* 2014; Shrestha *et al.,* 2017).

**Oral Hypoglycemic Agents**

- Biguanides: Metformin is first-line therapy for type II DM, reducing hepatic gluconeogenesis and improving insulin sensitivity (Rena *et al.,* 2017).
- Thiazolidinediones: Improve insulin sensitivity by enhancing adipogenesis and reducing circulating fatty acids (Greenfield and Chisholm, 2004).
- Sulfonylureas: Stimulate insulin secretion from β-cells by closing ATP-sensitive $K^+$ channels, leading to membrane depolarization and calcium influx (Sweetman, 2002; Ling *et al.,* 2006).

**Injectable Hypoglycemic Agent – Insulin**

Insulin therapy is used when oral agents fail or in type I DM. It enhances glucose uptake by activating receptor tyrosine kinase pathways. Insulin therapy is associated with drawbacks such as hypoglycemia, weight gain, lipohypertrophy, and injection-site discomfort (Mehanna, 2005; Kaur and Badyal, 2008; Tasneem, 2013).

**Herbal Therapy in Regulating Diabetes Mellitus**

Use of medicinal plants for treating DM dates back to ancient times. Herbal remedies are widely used for their safety, cost-effectiveness, and multiple pharmacological properties (Gupta *et al.,* 2008; Bhushan *et al.,* 2010; Chauhan *et al.,* 2010; Osadebe *et al.,* 2014).

**Herbs with Antidiabetic Properties**

Numerous plants including *Catharanthus roseus, Syzygium cumini, Trigonella foenum-graecum, Lawsonia inermis, Dioscorea alata, Houttuynia cordata, and Lindernia ciliata* have shown hypoglycemic effects in experimental models, sometimes comparable to glibenclamide (Nammi *et al.,* 2003; Kumar *et al.,* 2008; Mowla *et al.,* 2009; Choubey *et al.,* 2010; Maithili *et al.,* 2011; Poolsil *et al.,* 2017; Reddy and Rani, 2019).

**Herbs with Antihyperlipidemic Properties**

Plant-derived compounds such as saponins and steroids reduce serum cholesterol, triglycerides, LDL, and VLDL while increasing HDL. Notable plants with antihyperlipidemic effects include *Phyllanthus reticulatus, Ricinus communis, Canscora perfoliata, Musa balbisiana, and Aloe megalacantha* (Ramesh and Pugalendi, 2005; Maruthappan and Shree, 2010; Matthew *et al.,* 2012; Hammeso *et al.,* 2019).

***Catharanthus roseus***

Phytochemicals Responsible

- Alkaloids: Vindoline, vindolicine, vindolinine, ajmalicine, serpentine.
- Flavonoids & phenolics : Kaempferol, quercetin, rutin.
- Tannins, saponins, terpenoids, glycosides.

**Mechanisms of Antidiabetic Action**

1. Hypoglycemic activity
   - Ethanolic and aqueous extracts of C. roseus leaves, flowers, and roots have shown a significant reduction in blood glucose levels in alloxan- and streptozotocin-induced diabetic rats.
2. Insulin secretion & β-cell protection
   - Certain alkaloids enhance insulin release from pancreatic β-cells and protect them from oxidative damage.
3. Improved glucose utilization
   - Extracts increase glycogen storage in liver and muscle, enhancing peripheral glucose uptake.
4. Antioxidant effect
   - Scavenging of free radicals reduces oxidative stress, a major contributor to diabetic complications.
5. Lipid profile improvement
   - Administration of extracts has been shown to reduce cholesterol, triglycerides, and LDL, while raising HDL levels in diabetic models.

**Scientific Evidence**

- **Aqueous leaf extract** lowered blood glucose in alloxan-induced diabetic rats (Nammi *et al.,* 2003).
- **Methanolic extract** showed dose-dependent hypoglycemic effect in STZ-induced diabetic models (Singh *et al.,* 2001).

- **Vindolicine**, a bisindole alkaloid from *C. roseus*, was reported to stimulate insulin secretion and enhance glucose uptake in muscle cells (Patel *et al.,* 2012).

***Syzygium cumini***

**Active Phytochemicals**

- Alkaloids: Jambosine, jambosoline.
- Glycosides: Jamboline.
- Flavonoids & polyphenols: Quercetin, myricetin, kaempferol, ellagic acid.
- Tannins & anthocyanins: Found especially in seeds and fruit peel.
- Essential oils, terpenoids, saponins.

**Mechanisms of Antidiabetic Action**

1. Hypoglycemic effect
   - Seed and leaf extracts reduce fasting and postprandial blood glucose in experimental diabetic animals and in some human trials.
2. Insulin secretion & β-cell protection
   - Active compounds stimulate residual pancreatic β-cells to secrete insulin.
   - Provide protection against β-cell oxidative damage.
3. Delay in carbohydrate digestion & absorption
   - Polyphenols and glycosides inhibit α-amylase and α-glucosidase enzymes, slowing glucose absorption from the gut.
4. Improved glucose utilization
   - Enhanced glycogen storage in liver and muscle, supporting peripheral glucose uptake.
5. Antioxidant & anti-inflammatory effects
   - Strong free radical scavenging activity reduces oxidative stress, a major factor in diabetes-related complications.
6. Lipid profile improvement
   - Seed extracts lower cholesterol, triglycerides, LDL, and increase HDL in diabetic models.

**Scientific Evidence**

- Seeds: Ethanolic seed extracts significantly reduced blood glucose and improved lipid profile in streptozotocin (STZ)-induced diabetic rats (Heli *et al.,* 2015).
- Human studies: Powdered seed supplementation reduced fasting blood sugar and HbA1c levels in type 2 diabetic patients (Sharma *et al.,* 2012).
- Leaves: Methanolic extracts showed inhibition of α-glucosidase and α-amylase enzymes (Ayyanar & Subash-Babu, 2012).

- Anthocyanins in fruit pulp and peel also showed insulin-sensitizing and antioxidant effects.

**Trigonella foenum-graecum**

**Active Phytochemicals**

- Alkaloid: Trigonelline.
- Steroidal saponins: Diosgenin, yamogenin.
- Amino acid derivative: 4-hydroxyisoleucine (unique to fenugreek seeds).
- Galactomannan (soluble fiber).
- Polyphenols: Quercetin, apigenin, luteolin.
- Coumarins, flavonoids, nicotinic acid, ascorbic acid.

**Mechanisms of Antidiabetic Action**

1. Insulin secretion & sensitization
    - 4-hydroxyisoleucine directly stimulates insulin release from pancreatic β-cells in a glucose-dependent manner.
    - Improves insulin sensitivity in peripheral tissues.
2. Delay in carbohydrate absorption
    - High soluble fiber (galactomannan) slows gastric emptying and intestinal glucose absorption, reducing postprandial hyperglycemia.
3. Glucose metabolism improvement
    - Increases glycogen synthesis in liver and muscle.
    - Enhances activity of enzymes involved in glycolysis and glycogenesis.
4. Inhibition of carbohydrate-digesting enzymes
    - Inhibits α-amylase and α-glucosidase, slowing carbohydrate breakdown.
5. Antioxidant effect
    - Polyphenols and flavonoids reduce oxidative stress, protecting β-cells and preventing complications.
6. Lipid profile regulation
    - Lowers serum cholesterol, triglycerides, LDL, while raising HDL.

**Scientific Evidence**

- Animal studies: Fenugreek seed powder significantly reduced blood glucose in alloxan- and STZ-induced diabetic rats (Basch *et al.,* 2003).
- Human clinical trials:
    - Daily intake of 10–25 g fenugreek seed powder reduced fasting blood glucose, postprandial glucose, and HbA1c in type 2 diabetics (Sharma *et al.,* 1996; Gupta *et al.,* 2001).

- Fenugreek seed extract enriched with 4-hydroxyisoleucine improved glucose tolerance and insulin sensitivity in patients with mild type 2 diabetes.

***Carica papaya Linn.***

**Active Phytochemicals**

- Alkaloids: Carpaine, pseudocarpaine.
- Flavonoids: Quercetin, kaempferol, myricetin.
- Phenolic compounds: Caffeic acid, ferulic acid.
- Saponins, tannins, glycosides.
- Vitamins & minerals: Vitamin C, E, β-carotene, magnesium, zinc.

**Mechanisms of Antidiabetic Action**

1. Hypoglycemic activity
    - Leaf and seed extracts reduce fasting blood glucose in diabetic animals.
2. Insulin secretion & β-cell protection
    - Flavonoids and alkaloids enhance insulin release and protect pancreatic β-cells from oxidative stress.
3. Antioxidant effect
    - Strong free radical scavenging activity reduces oxidative damage in diabetic conditions, helping to prevent complications.
4. Enzyme inhibition
    - Extracts inhibit α-amylase and α-glucosidase, slowing carbohydrate breakdown and glucose absorption.
5. Improved lipid profile
    - Reduction of cholesterol, triglycerides, and LDL; elevation of HDL in diabetic models.
6. Hepatoprotective effect
    - Papaya leaf extract improves liver enzymes and glycogen storage, which helps regulate glucose metabolism.

**Scientific Evidence**

- Leaves:
    - Aqueous leaf extract lowered blood glucose and improved insulin sensitivity in alloxan-induced diabetic rats (Juárez-Rojop *et al.,* 2012).
    - Methanolic leaf extract showed α-glucosidase inhibitory activity, reducing postprandial glucose spikes.
- Seeds:
    - Ethanolic seed extract demonstrated hypoglycemic and lipid-lowering effects in streptozotocin-induced diabetic rats (Oloyede *et al.,* 2011).

- Fruit:
    - Unripe papaya pulp has shown mild hypoglycemic effects, but ripe fruit is more supportive as an antioxidant rather than a strong hypoglycemic agent.

**Conclusion:**

Diabetes mellitus remains a significant global health issue affecting both humans and animals. Current therapies, though effective, are associated with several limitations, thereby encouraging the search for safer and cost-effective alternatives. Herbal medicines, particularly have shown promising antidiabetic and antihyperlipidemic effects, alongside numerous other pharmacological properties, supporting their potential role in diabetes management

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# ABIOTIC STRESSOR: A MODERN TOOL FOR DEVELOPMENT OF AGRICULTURE, HORTICULTURE AND ANIMAL HUSBANDRY

**Punam Dnyandeo Lonkar[1], Shamal Sabaji Mhaske[1],**
**Aniket Pramod Phadtare[2] and Ajit Sopan Masurkar*[3]**
[1]Department of Zoology and Research Centre,
New Arts Commerce and Science College Ahmednagar, Maharashtra414 001
[2]Department of Zoology,
Government Gandhi College, Balaji Mihona, Bhind, Madhya Pradesh, 477441
[3]Applied Biology Division,
CSIR-Indian Institute of Chemical Technology, Tarnaka, Hyderabad, Telangana 500 007
*Correspondence author E-mail: ajitmasurkar1212@gmail.com

**Abstract:**

Understanding and strategically manipulating physical and chemical stressors in agriculture, horticulture, and animal husbandry presents promising opportunities to enhance productivity, resilience, and sustainability. Emerging techniques such as seedling priming with ultraviolet (UV) radiation and controlled exposure to drought or salinity stress have demonstrated the ability to induce beneficial physiological and molecular responses in plants, leading to improved nutritional content, stress tolerance, and yield stability. Similarly, in animal husbandry, moderate environmental stressors can stimulate immune function and improve overall health and productivity. This integrative approach, which leverages controlled stress exposure, offers a cost-effective, environmentally friendly method to bolster crop and livestock performance, particularly under the increasing pressures of climate change. By advancing our understanding of stress-induced adaptation mechanisms, future farming systems can better optimize resource use, improve food quality, and ensure sustainable food security for a growing global population.

**Keywords:** Abiotic Stress, Agriculture, Animal Husbandary, Horticulture, Chemical Stress, Physical Stress, Food Security, Sustainable Development.

**Introduction:**

Global food and nutritional security rely heavily on the interconnected pillars of agriculture, horticulture, and animal husbandry, which together support ecological balance and sustain billions of livelihoods. However, these systems face constant challenges from abiotic stressors—non-living environmental factors such as drought, salinity, temperature extremes, and soil degradation—that significantly limit productivity and yield. While traditionally viewed as harmful, especially as climate change intensifies their impact, controlled or moderate exposure to these stresses can actually enhance resilience and quality through adaptive responses in plants and animals. This concept of "stress priming" leverages natural defense mechanisms to improve water-use efficiency, nutrient uptake, immune function, and the nutritional and sensory qualities of crops and livestock products. Harnessing abiotic stress as a developmental tool opens new pathways for breeding climate-resilient varieties, advancing biotechnology, and developing climate-smart agricultural practices that ensure sustainability and food security amid an increasingly unpredictable environment.

**A. Physical Stressor**

Physical stressors are non-living environmental factors like drought, extreme temperatures, flooding, and excessive light that physically challenge plants and animals. They can disrupt vital processes such as water uptake and metabolism, often harming growth and productivity. However, moderate exposure to these stressors can trigger adaptive responses that improve resilience and survival.

**Advantages of Physical Stressors:**

1. Can stimulate plants and animals to develop stronger adaptive and defense mechanisms, enhancing resilience.
2. Moderate stress (like drought or temperature changes) can improve crop quality by increasing valuable compounds such as antioxidants, flavonoids, and vitamins.
3. Used as tools in research and breeding to develop stress-tolerant varieties.
4. Controlled stress applications (e.g., regulated irrigation or temperature) can improve resource use efficiency and product shelf life.

**Disadvantages of Physical Stressors:**

1. Excessive or uncontrolled stress leads to reduced growth, lower yields, and poor product quality.
2. Can cause physiological damage, such as wilting, tissue injury, or impaired nutrient uptake.
3. Increased susceptibility to pests, diseases, and overall weakened plant and animal health.
4. In animal husbandry, physical stress like heat or cold stress can lower productivity, reproduction rates, and immunity, leading to economic losses.

**1. Drought Stress: Challenges and Benefits**

Drought negatively impacts plants by causing water deficiency, which leads to reduced photosynthesis, impaired nutrient uptake, stunted growth, and lower crop yields (Anjum *et al.,* 2011). It can also cause wilting, leaf scorch, and increased susceptibility to pests and diseases. In severe cases, prolonged drought can result in plant death and significant losses in agricultural productivity. In water-scarce regions, methods like controlled deficit irrigation and drought priming enhance plant adaptation and resource allocation, boosting productivity and survival.

Measured drought stress improves fruit quality and shelf life in horticulture by increasing water usage efficiency and encouraging the buildup of secondary metabolites like flavonoids and antioxidants. Crops subjected to drought have altered leaf structures and deeper root systems, which maximize water uptake and reduce transpiration loss. A study by Sarker and Oba (2018) demonstrated that despite being a negative regulator of plant development, drought stress enhances the nutritional and antioxidant properties of *Amaranthus* leafy vegetables, making them valuable and health-promoting crops for semi-arid regions. According to recent studies, drought stress increased secondary metabolites, including the betacarotene composition of Choysum varieties (Hanson et al.,2011), vitamin C in tomato (Stagnari *et al.,* 2016), total polyphenol and total flavonoid content in buckwheat (Siracusa eta l., 2017), total antioxidant activity, total polyphenol and total flavonoid content in *Achillea* species (Gharibi *et al.,* 2016). As a result, drought stress is an excellent way to increase the nutritional value of vegetables.

Drought stress harms plant growth but, when managed, can improve crop resilience and enhance nutritional quality, offering benefits for sustainable agriculture in dry regions. These nutrient-rich plants also offer valuable feed options to boost production in animal husbandry.

**2. Temperature Stress and Food Security:**

Rising global temperatures negatively impact food security by causing heat stress in crops, livestock, poultry, and fisheries, which reduces growth, productivity, and quality, disrupts reproductive cycles, lowers nutrient availability, and increases vulnerability to pests and diseases, ultimately threatening agricultural yields and livelihoods worldwide (Rizwan, 2023).

Uncontrolled Heat stress severely affects poultry growth, egg production, and quality worldwide (Biswal *et al.,* 2022). Cold stress adversely affects crops, livestock, poultry, and fisheries by slowing growth, damaging tissues, impairing metabolic and reproductive functions, reducing nutrient uptake, and increasing susceptibility to diseases, which collectively lead to lower productivity and threaten food security in affected regions (Upadhyay, (2017.).

Temperature stress can be a regulated and beneficial research technique for improving resistance and adaptation in plants and animals, despite being typically thought of as a major abiotic constraint on output. Short-term cold stress triggers salicylic acid–dependent responses in *Arabidopsis*, enhancing resistance to certain pathogens (Wu *et al.,* 2019). In agriculture, high temperatures are used to sterilize soil, tools, and seeds, reducing pests and diseases, while low temperatures help preserve harvested crops by slowing spoilage and extending shelf life. In horticulture, heat sterilizes growing media and equipment to prevent disease, and cold storage maintains the freshness and quality of fruits and vegetables. In animal husbandry, heat is used to sterilize housing and equipment, while low temperatures are essential for safely storing animal products like milk, eggs, and meat, ensuring food safety and quality.

## 3. Stress from Radiation

Radiation stress, traditionally viewed as harmful to ecosystems, plants, and animals, is now being reconsidered for its potential benefits in agriculture and animal husbandry when applied in controlled, low doses. Ionizing radiation (such as X-rays, gamma rays, and heavy-ion beams) and solar radiation (including UV rays and high light intensity) can induce physiological and genetic changes that enhance resilience, productivity, and quality. Recent research highlights the advantages of low-dose radiation in improving seed germination, inducing beneficial mutations, extending shelf life, sterilizing feed and water, and ensuring food safety through pathogen elimination. These findings support the strategic use of radiation as a tool for sustainable agricultural and livestock practices.

Ultraviolet radiation (UVA and UVB) effectively enhances the nutraceutical content of fruits and vegetables by triggering plant stress responses that stimulate the accumulation of health-promoting secondary metabolites, contributing to the prevention of chronic diseases and improving the functional quality of horticultural crops (Jacobo-Velázquez *et al.,* 2022). According to Hayat *et al.,* (2024), Infrared (IR) radiation, with wavelengths from 760 to 10,000 nm, is emerging as a promising tool in poultry production by enhancing growth performance, gut health, immune response, and food safety through applications such as heating, spectroscopy, beak trimming, and therapeutic treatments, offering an innovative approach to improve productivity, efficiency, and animal welfare in the industry.

Seedling priming with UV-A radiation is a simple, cost-effective, and environmentally friendly technique that enhances water stress tolerance in tomato and bell pepper plants by significantly improving root biomass, fruit yield, and stress-related biochemical responses such as proline, phenolic compounds, and chlorophyll content, thereby mitigating the adverse effects of water deficit (Escobar-Hernandez *et al.,* 2024).

Controlled low-dose radiation, despite its potential toxicity and hazards at high levels, offers promising, eco-friendly strategies to enhance crop resilience, nutritional quality, and poultry health, making it a valuable tool for sustainable agriculture and animal husbandry when used responsibly.

## 4. Soil Salinity

Salinity stress is a major global problem that severely limits agricultural productivity by reducing crop growth, nutrient uptake, and yield, especially in arid and semi-arid regions, posing a significant threat to food security worldwide. Salinity stress negatively impacts agriculture, horticulture, and animal husbandry by reducing crop germination, growth, and yield due to toxic ion accumulation and osmotic imbalance; in horticulture, it lowers fruit quality and plant vigor, while in animal husbandry, it decreases the nutritional quality of forage and water availability, leading to poor livestock health, reduced productivity, and increased vulnerability to diseases.

(Türkan &Demiral, 2009) reported that salinity stimulate generation of ROS causing oxidative stress resulting increased phenolic compounds and antioxidant activity of plants. Salinity stress, while often harmful to plant growth and germination, can be strategically used to enhance the nutritional profile of crops by increasing valuable compounds like vitamins, phenolics, and flavonoids, as seen in *Salvia hispanica* (Younis *et al.,* 2021). These nutrient-enriched plants not only offer improved health benefits for human consumption but also serve as higher-quality feed for livestock in animal husbandry, potentially boosting animal health, productivity, and resilience. Thus, managing salinity stress in crops can have a positive ripple effect, supporting both sustainable agriculture and more nutritious, efficient animal production systems.

**B. Chemical Stressor**

Natural environments expose plants and animals to many chemical stressors, which can impair physiological and metabolic processes. These chemically generated abiotic stresses, such as heavy metal contamination, salinity, pesticide residues, and atmospheric pollutants, not only impair food intake and water balance, but also cause oxidative stress by producing an excess of reactive oxygen species (ROS). As a result, critical functions including as photosynthesis, respiration, and cellular homeostasis are disrupted, resulting in slower growth, developmental abnormalities, and severe agricultural yield and productivity losses. The compounded nature of these stressors in the field makes it extremely difficult for plants to adjust, emphasizing the importance of integrated techniques, such as chemical priming or the application of biostimulants, to improve plant resilience and agricultural productivity. Abiotic stressors have a negative effect on plant growth and productivity. Chemical-induced abiotic stress, which is commonly regarded as harmful, is increasingly becoming acknowledged as a developmental tool in agriculture, horticulture, and animal husbandry, particularly when used in controlled or moderated amounts. According to recent research, chemical priming is a new and promising technique to crop stress management, providing a proactive strategy for increasing plant resilience under abiotic stress conditions. The advantages and disadvantages of chemically-induced abiotic stress as a development tool for agriculture, horticulture, and animal husbandry are as follows:

**Advantages:**

1. **Enhanced Stress Tolerance:** Controlled chemical-induced abiotic stress can stimulate plants and animals to develop greater tolerance to adverse environmental conditions such as drought, salinity, and temperature extremes.
2. **Improved Productivity:** By priming crops or livestock through mild stress, growth and yield may improve, leading to better resource use efficiency.

3. **Quality Improvement:** In horticulture, stress induction can enhance the production of secondary metabolites, such as antioxidants and flavors, improving nutritional and commercial value.
4. **Disease Resistance:** Abiotic stress can sometimes activate defense pathways, making plants more resistant to pests and diseases.

**Disadvantages:**

1. **Potential Toxicity:** Chemical stressors can be harmful if not carefully controlled, causing damage or reduced growth instead of benefits.
2. **Environmental Concerns:** Overuse of chemicals may lead to soil and water contamination, harming ecosystems.
3. **Animal Welfare Issues:** In animal husbandry, chemical-induced stress can negatively impact animal health and welfare if mismanaged.
4. **Cost and Management Complexity:** Applying and managing chemical stress requires expertise and resources, which may not be feasible for all farmers or producers.

Chemically induced abiotic stress can be applied through techniques like seed priming, pre-harvest sprays, and post-harvest treatments. Seed priming improves stress tolerance and germination, while pre-harvest and post-harvest applications help enhance plant resilience, quality, and shelf life. Similar approaches in animal husbandry can improve stress management and productivity, making these methods valuable for agriculture and farming.

**Seed Priming:** Seed priming is an useful tools in agriculture and horticulture that prepares seeds for faster and more uniform germination. As a developmental aid, it improves plant tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity by activating stress defense mechanisms at an early stage. Seed priming, which originally involved soaking seeds in water to improve germination, now includes various chemical and non-chemical agents designed to enhance germination, growth, and stress tolerance, making it a valuable tool for improving crop resilience to climate change (MacDonald Mohan, 2025). This strategy enhances crop establishment, increases yield potential, and promotes sustainable farming by lowering the need for excessive chemical inputs. According to Nguyen *et al.* (2018), plants can be primed with certain chemical agents such as salicylic acid, jasmonic acid, hydrogen peroxide, or proline, which activate their defense mechanisms without inflicting major physiological damage. This primed state allows faster and stronger reactions when the plant is later exposed to environmental stress, such as heavy metals. In addition to improving osmolyte accumulation and antioxidant capability, chemical priming also modifies important gene expression pathways linked to stress, which improves growth and yield in stressful environments. The development of stress-tolerant crop varieties can be facilitated by purposefully exposing plants to chemical stressors, such as salinity, heavy metals, or particular biostimulants, which can activate antioxidant defense systems, induce stress adaptation mechanisms, and improve physiological resilience. Seed priming with ZnO (nano or bulk) boosts wheat drought tolerance by enhancing antioxidant defenses and osmoprotectants (El-Shazoly *et al.,* 2025). According to recent research, chemicals like citric acid, salicylic acid, and humic compounds not only reduce chemical stress but also increase plant vigor and output in challenging environments (Youssef *et al.,* 2025). Yan *et al.,* (2024) noted that graphene oxide seed priming improves peanut germination, enhances salinity tolerance, and increases pod yield by boosting antioxidant activity and nutrient metabolism. Chemical-induced abiotic stress can therefore be strategically used to create climate-resilient agricultural systems, enhance crop and animal performance, and support sustainable food production under increasingly challenging environmental conditions.

**Pre Harvest Treatment:** Pre-harvest treatments are the application of physical, chemical, or biological agents to crops and animals prior to harvest in order to improve yield, quality, and shelf life. They play an important role in agriculture, horticulture, and animal husbandry by increasing crop and livestock productivity, quality, and resilience. In agriculture and horticulture, these treatments include the application of nutrients, plant growth regulators, biostimulants, or protective chemicals prior to harvest to increase productivity, stress tolerance, and postharvest shelf life. Using a preharvest sodium nitroprusside spray at 100 µM can improve the shelf life of ber fruit to 21 days by preventing rotting and increasing antioxidant activity (Sharma &Bons 2025). While Salicylic acid (SA) application improved yield and fruit quality in sweet cherry under deficit irrigation by reducing fruit cracking and enhancing post-harvest storage. It helped maintain fruit weight and quality for up to 30 days, showing its potential as a stress mitigation tool (González-Villagra *et al.,* 2024). Sangari *et al.* (2021) reported that adding organic acid salts (OAS) to plant protein-rich diets, namely 5 g/kg sodium propionate, increased development, feed efficiency, and blood health in juvenile yellowfin seabream (*Acanthopagrus latus*). These findings indicate that OAS supplementation improves fish welfare and performance without changing body composition. Similarly, Supplementing broiler diets with mixed organic acids (MOA), especially at 3000 mg/kg, improves growth performance, meat quality, fatty acid composition, and intestinal health. These benefits suggest MOA as a promising natural feed additive for enhancing broiler production ( Ma *et al.,* 2021). Antibiotic misuse in poultry has raised resistance and safety concerns, prompting the EU to promote alternatives like polyphenols and organic acids. These natural additives show antimicrobial and growth-promoting effects, but more research is needed, especially for laying hens (Scicutella *et al.,* 2021). The use of pre-harvest chemical treatment is not confined to fisheries and poultry; it has also boosted dairy production. Supplementing dairy goat diets with organic acids and pure botanicals enhances milk fat content and coagulation while preserving metabolic health, underlining their potential as feed additives (Giorgino *et al.,* 2023). Exogenous pre-harvest treatments, such as the application of plant growth regulators, micronutrients, or biostimulants, have been shown to significantly influence the physiological processes of leguminous plants. These treatments can enhance biological activity and stimulate the synthesis of beneficial metabolites, including proteins, amino acids, and antioxidants. As a result, legumes become more nutrient-dense, improving their quality as a food source. This not only boosts the health benefits of consuming legumes but also supports efforts to promote sustainable agriculture and ensure a nutritious diet (Liu *et al.,* 2019).Recently, several studies have shown that chemically induced abiotic stress such as salinity stress affects the quality and nutritional value of buckwheat (Lim *et al.* 2012), radish (Yuan *et al.* 2010), wheat (Cuong *et al.* 2020) and rapeseed sprouts (Falcinelli *et al.* 2017). 100 mMNaCl treatment enhances nutritional value of *Vignaradiata* sprouts with reduction in fresh weight (Koodkaew 2019). Thus, pre-harvest treatments, when applied appropriately, serve as valuable tools to support sustainable and resilient production systems across all three sectors**.**

**Post Harvest Treatment:** Post-harvest chemical treatments are commonly employed in agriculture, horticulture, and even animal husbandry to preserve product quality, reduce losses, and maintain nutritional content. Chemicals such as fumigants, fungicides, and preservatives are used on grains, legumes, fruits, and vegetables to control pests, prevent microbiological deterioration, and improve shelf life during storage and transportation. This provides a consistent supply of high-quality crops for human consumption and animal feed. Pomegranate fruits often face high postharvest losses, impacting quality and profitability despite available treatments. While chemical fungicides can help, their health and environmental risks are a concern. Natural compounds like putrescine, oxalic acid, and methyl jasmonate have shown promise in reducing spoilage and extending shelf life, highlighting the need for safer, more effective postharvest solutions to enhance storability and preserve nutritional value (Opara et al.,2015). Natural organic acids have shown significant promise as preservatives for enhancing the quality of postharvest fruits. In recent years, applying these organic acids externally has become an effective method to maintain fruit quality and prolong shelf life. In animal husbandry, the quality and safety of feed crops, which are frequently handled after harvest, have a direct impact on animal health and productivity. Thus, prudent use of post-harvest chemical treatments promotes food security, increases economic efficiency, and adds to the long-term viability of integrated agricultural systems.

Chemical processing in postharvest treatment, such as the use of synthetic fungicides and pesticides, poses risks to human health and the environment due to potential toxic residues and pollution. These concerns have driven the search for safer alternatives, including natural compounds like organic acids, polyamines, and plant extracts, which effectively reduce spoilage and extend shelf life without harmful side effects. Adopting such natural treatments supports sustainable agriculture and food safety while maintaining product quality.

**Conclusion:**

Controlled use of physical and chemical stressors presents a promising avenue to enhance resilience, productivity, and quality in agriculture, horticulture, and animal husbandry. By leveraging these stressors strategically, future farming practices can become more sustainable and adaptive to climate challenges, ultimately supporting global food security and improved livelihoods.

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# SUSTAINABLE LAND MANAGEMENT IN WATERSHED AREAS USING DIGITAL TECHNOLOGIES

**Geeta Kalaghatagi*[1], T H V Meghana[1], Raju Chavan, Sneha Sangappa Benal[1] and Sajjan. G[1]**

[1]Department of Agronomy, University of Agricultural Sciences, Dharwad

[2]Department of Agroforestry, University of Agricultural Sciences, Dharwad

*Corresponding author E-mail: geetakalaghatagiedu@gmail.com

**Abstract:**

Increasing the productivity on small scale farms in developing countries like India is a critical part of a solution to the food insecurity problem. To face all these new challenges, increasing the productivity level of a pollution-free product is inevitable. This can be realized by applying advanced, environmentally friendly technologies, which can manage and allocate all resource efficiently for sustainable development of agriculture [3]. Precision Agriculture (PA) is such as a new emerging, highly promising technology that is spreading rapidly in the developed countries. But rapid changes in the socio-economic pattern of some developing countries, such as India, China, and Brazil, created new scope and opportunities for PA to be applied in these countries.

**Introduction:**

**Components of Precision Farming**

**Steps in Precision Farming:** The three basic steps in precision farming are Assessing Variability, Managing Variability and Evaluation, which are described as:

**Assessing Variability:** In precision farming, inputs are to be applied precisely in accordance with the existing variability. Therefore, assessing the variability in field as very crucial and first step of precision agriculture. Spatially infield variability can be measured by using sensors, yield monitors etc. with help of Global Positioning System (GPS) system.

**Managing Variability:** After assessing the spatial variability, the same can be taken care of through precision and leveling, variable rate technology, site specific planting, site specific nutrient management precision water management, site specific weed management and precision pests and disease management etc. These precision farming practices aims at managing the variability by applying and making farm inputs available only in required quantities, at particular time and at specific locations.

**Evaluation**: There are three important issues regarding precision agriculture evaluation namely economics, environment and technology transfer.

**Different Approaches for Precision Agriculture:** There are three main approaches (grid sampling, management zones for large fields and clustering zones for small fields), whereby crop inputs can be distributed on a spatially selective basis.

**Grid Sampling**: It was the very first approach used to develop precision application maps. The fields are sampled along a regular grid at sample spacing ranging from 60-150m depending on the field size and the samples are analyzed for desired properties. The results of these analyses are interpolated to unsampled location by geo-statistical techniques viz Kriging and Inverse Distance Weighing (IDW) and the interpolated values are classified using Geographic information System (GIS) techniques in to limited number of management zones. The boundaries of management zones are then visualized using mapping software and management recommendations are developed for each zone.

**Management Zones**: A more economically feasible approach that divides fields in to different regions referred to as production level management zones has been established recently in US [1].The delineation of management zones uses three GIS data layers viz. bare soil imagery, topography and farmer's experience. A field can be divided into three different zones: high, medium and low based on the productivity of the area and the crop inputs can be applied accordingly.

**Random Sampling and clustering Zones:** Field size is very small in India as compared to the western countries, as the majority being small and marginal farmers with continuous subdivision and fragmentation of land. Therefore, the field sampling and production level management zone approach may not be feasible in Indian agriculture. The different small field in possession of a farmer or farmers may be considered as management zones and the recommendations could be based on random sampling from each zone.

**Spectral Reflectance Measurements:** Traditionally ground measurements of plant parameters for example leaf area and biomass are usually tedious and costly. By using new techniques, collecting data of plant and soil parameters have many advantages over traditionally ground measurements by using old and known techniques. Thus, there have been numerous studies conducted to determine plant parameters by utilizing the spectral features of leaf reflectance. All incident light energy on any surface is reflected, absorbed or transmitted. The reflectance is the ratio of the amount of the light reflected from the plane to the irradiance to the plane [7][4] stated that determined leaf light reflectance and transmittance based on the critical reflection of visible light at the cell wall air interface of spongy mesophyll tissue[9]. Leaf with a compact mesophyll structure would reflect less light than a leaf with a spongy mesophyll, therefore, the less hydrated cell wall air interface of the mesophyll structure.

**Ground Based Hyperspectral Image Processing (HIP)**

A ground based hyperspectral data analysis is a supporting tool for remote sensing technology. The chlorophyll a, chlorophyll b, and carotenoids are interrelated to the physiological function of the plant leaves and act as a very important role in growth. Continuous removal method is used to extract the absorption features for chlorophyll b and carotenoids pigment contents in rice leaves and panicles. The reflectance curves of leaves and panicles at different stages can be measured with a ground based hyperspectral analysis using ASD (Analytical Spectral Device) spectro-radiometer that obtains continuous spectra from 300nm to 2500 nm. The benefits of EO-1 Hyperion hyperspectral data to agriculture have been studied in Australia.

**Remote sensing for Precision Farming**

Remote sensing technology that allows non-destructive acquisition of information about the Earth's surface can facilitate the implementation of PA. For example current crop status (including maturity period) and crop stresses such as nutrient and water stress, disease, pest and weed infestations can be discerned by means of remote sensing instruments such as cameras, laser scanners, linear arrays and area arrays, without actually being in contract with them. Information fathered via different sensors and referenced using a Global Positioning System (GPS) can be integrated to create field management strategies for chemical application, cultivation and harvest.

**Commercial Optical Sensors**

Tools developed in the world over have provided an excellent opportunity for real time N management strategies for different crops especially for rice and wheat. A handheld Green Seeker ™ optical sensor unit (NTech Industries Incorporation, Ukiah, CA USA) is already being used for NDVI measurement of field crops. The N-Sensor, developed by the European Company Yara, is also used commercially in Europe by 350 growers and contractors. Fitted to the roof of the tractor it scans crops and automatically regulates the rate of nitrogen fertilizer spread according to the greenness of the crop. This multispectral scanner measures the light reflectance properties of the crop canopy. Recently commercialized active ground-based sensors eliminate the need for frequent calibration and overcome the problems of cloud cover and limitations of the time of day when measurements are made (i.e. natural illumination and shadow). The polychromatic bank of Light Emitting Diodes (LEDs) used in the Crop Circle ACS-210 (Holland Scientific, Lincoln, NE) sensor emits light in two wavebands, visible (595 nm) and NIR (880 nm)

**Variable Rate Technology (VRT)**

Variable Rate Technology is the technique of applying the farm inputs such as seeds, fertilizer, pesticides etc. in varying rates at the places and amounts where they are required to produce uniform yields throughout the entire field. The variable rate seed drills and planters, fertilizers spreaders and sprayers are commercially available. Farm machineries equipped with VRT generally possess a Differential Global Positioning System (DGPS) receiver to locate the spatial variability in the field and automatically regulate the rate of application. Due to high cost of integrated control systems, the farmers prefer to rely on custom hiring for using VRT. The most important and widely used form of VRT is variable rate fertilizer application.

**Yield Monitoring**

In Punjab, the total area under combine harvesting for rice and wheat is 91% and 82% respectively. Combine harvesters are also going to be popularize in other parts of India especially on custom hiring basis. About 90-95% of total 425 thousand combines operated in India are on custom hiring basis. The yield data is displayed over the display unit having bright Red LED display Unit EPS 301 with 24 bit sigma delta converter installed near the seat of the driver. Software developed for grain weight measurement for one revolution of the rear wheel of the combine. Methodology is developed for harvested area calculation by using GPS. The variable yield maps for the harvested rice crop were generated by using the yield monitor fitted combine harvester.

**Steps to Precision Agriculture Success:**

- The first step to success is determining whether there is a need for precision agriculture at enterprise (Farm/Poultry or Dairy farm).
- The second step is determining the specific requirements that will fulfill the identified need or needs.
- Once the requirements have been enumerated, the third step is to identify the personnel within enterprise who are going to use PA tools.
- The fourth step to success is training and support to the identified personnel
- The fifth step is back-up, whether in the form of an alternate plan to do something or just archiving important information.

**Precision Technologies already adopted by Indian farmers**

Laser and leveler, Tensiometer, Leaf Color Chart (LCC), paired row trench planting technique, micro-Irrigation methods were recommended in India or specially for Indo-Gangetic plains for precision farming to enhance on farm water use efficiency and other farm inputs for better yields. Farmers are adopting in a big way the laser leveling technology and micro-irrigation systems at their field. Other foremost step for managing soil and yield variability could be the management of landscape variability through precision land leveling. Significant increase in the agronomic efficiency of the applied N, P, and K was recorded in rice due to precision land leveling compared to traditional leveling.

Punjab Agricultural University, Ludhiana has successfully demonstrated this technology over 300 acres at different farmer's field in the district Jalandhar, Ludhiana, Sangrur, Moga, Patiala and Fategarh Sahib during 2005-06. Fertigation (application of fertilizer solution with drip irrigation) has the potential to ensure that the right combination of water and nutrients is available at the root zone, satisfying the plants total and temporal requirements of these two inputs. Fertigation saves fertilizer as it permits applying fertilizer in small quantities at a time matching with the plant's nutrient need. Besides it is considered eco-friendly as it avoids leaching of fertilizers.

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# NANO-AGRICULTURE: A NEW FRONTIER IN CROP PRODUCTION AND PROTECTION

**Varala Krishnaveni*[1], Rama Krishna V[2] and Sathish Kota[3]**

[1]Department of Plant Pathology,

Vasantrao Naik Marathwada Krishi Vidyapeeth University, Parbhani, Maharashtra, 431402.

[2]Department of Agricultural Extension Education, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad-500030

[3]Department of Agricultural Entomology,

Indira Gandhi Krishi Vishwavidyalaya (IGKV), Raipur, Chhattisgarh-492012

*Corresponding author E-mail: varalakrishnaveni4444@gmail.com

**Abstract:**

The increasing global population and environmental challenges demand innovative and sustainable agricultural practices. Conventional farming, heavily reliant on chemical fertilizers and pesticides, has led to soil degradation, environmental pollution, and rising resistance in pests and pathogens. Nano-agriculture, the application of nanotechnology in crop production and protection, offers a promising solution. By utilizing nanoparticles, nanomaterials, and nanosensors, it enables precise nutrient delivery, targeted pest management, enhanced crop protection, and real-time monitoring of soil and plant health. This chapter provides a comprehensive overview of nano-agriculture, exploring key applications such as nano-fertilizers, nano-pesticides, smart delivery systems, and nanosensors, along with recent advancements across different crops. It also discusses the benefits, challenges, and future prospects of nano-agriculture, emphasizing its potential to increase productivity, optimize resource use, reduce environmental impact, and enhance food quality. With continued research, technological innovation, and appropriate regulatory support, nano-agriculture is poised to play a pivotal role in achieving sustainable farming and global food security.

**Keywords:** Crop Protection, Nano-Fertilizers, Nano-Pesticides, Nano-Technology, Precision Agriculture, Sustainable Agriculture

## Introduction:

Agriculture, the backbone of human civilization, is under increasing pressure to meet the food demands of a rapidly growing global population while ensuring environmental sustainability. Traditional farming practices, although productive in the past, have resulted in several ecological challenges, including soil degradation, water pollution, and loss of biodiversity (Scott and Chen, 2020). At the same time, the indiscriminate use of chemical fertilizers and pesticides has created a dual crisis of reduced efficiency and growing resistance in pests and pathogens (Gogos *et al.,* 2012).

In this context, nanotechnology has emerged as a transformative approach, capable of addressing agricultural challenges with greater precision, efficiency, and sustainability. The application of nanotechnology in agriculture—commonly referred to as nano-agriculture—involves the use of nanoscale materials and devices to enhance crop production and protection. By leveraging the unique physicochemical properties of nanoparticles, such as high surface-to-volume ratio and controlled release mechanisms, nano-agriculture promises to improve crop yields, reduce agrochemical residues, and optimize resource utilization (Kah *et al.,* 2019).

This chapter explores the concept of nano-agriculture, its applications, benefits, challenges, and future prospects, providing a comprehensive overview of how nanotechnology may revolutionize global food systems.

**Nano-Agriculture**

Nano-agriculture refers to the application of nanoparticles, nanomaterials, and nanodevices in various aspects of farming, including soil management, crop nutrition, pest control, and disease resistance. Unlike conventional inputs, nano-enabled agricultural products are designed to act at the molecular or cellular level, ensuring targeted action and higher efficiency (Rai *et al.,* 2015).

Nanoparticles can serve as carriers for nutrients or pesticides, enabling controlled release and improved bioavailability. Nanosensors can be embedded in soils or plants to monitor real-time changes in nutrient status, moisture, or pathogen presence. Together, these tools enable precision farming, where resources are applied only when and where needed, thereby minimizing waste.

**Applications of Nano-Agriculture**

**1. Nano-Fertilizers**

Conventional fertilizers often exhibit low nutrient-use efficiency, with less than 40% of applied nitrogen and phosphorus being taken up by crops (Table 1&2) (Tilman *et al.,* 2011). Nano-fertilizers are engineered to enhance nutrient absorption and reduce losses through volatilization or leaching. They can be tailored to release nutrients in response to soil or plant signals, thereby improving nutrient-use efficiency and reducing environmental pollution (Tarafdar *et al.,* 2013).

**2. Nano-Pesticides**

Overuse of chemical pesticides has harmed the environment and contributed to pest resistance. Nano-pesticides encapsulate active ingredients in nanoparticles, allowing controlled and sustained release (Table 3). This improves target specificity, reduces dosage requirements, and minimizes off-target effects (Kah *et al.,* 2013). Silver and silica nanoparticles possess strong antimicrobial activity against plant pathogens (Chhipa, 2017).

**3. Nano-Based Crop Protection**

Nanoparticles can deliver bioactive molecules, such as resistance-inducing proteins or RNA interference (RNAi)-based molecules, enhancing resistance against pathogens (Chen and Yada, 2011). Nanoparticle coatings can also protect seeds from fungal infection and improve germination under stress.

**Table 1: Comparison of Conventional Fertilizers and Nano-Fertilizers**

| Feature | Conventional Fertilizers | Nano-Fertilizers | Source |
|---|---|---|---|
| Nutrient release | Bulk release; often leaches | Controlled/sustained release | Tilman *et al.,* 2011; Tarafdar *et al.,* 2013 |
| Nutrient-use efficiency | Low (≤40%) | High (>70%) | Tilman *et al.,* 2011; Raliya *et al.,* 2016 |
| Environmental impact | High runoff, pollution | Reduced contamination | Kah *et al.,* 2018; Scott & Chen, 2020 |
| Targeting | Non-specific | Molecular/cellular level | Rai *et al.,* 2015 |
| Cost | Lower | Higher (initially) | Kumar *et al.,* 2019 |
| Application | Frequent | Less frequent, precision-based | Fraceto *et al.,* 2016 |

**Table 2: Recent Nanofertilizers in Different Crops**

| Crop | Nanofertilizer Type | Target Nutrient | Observed Benefit | Source |
|---|---|---|---|---|
| Rice | Nano-hydroxyapatite | Phosphorus | Increased P uptake and yield | Liu & Lal, 2015 |
| Wheat | Nano-urea | Nitrogen | Slow release, higher efficiency | Raliya *et al.,* 2016 |
| Maize | Zinc oxide nanoparticles | Zinc | Enhanced growth and chlorophyll | Raliya *et al.,* 2016 |
| Tomato | Iron oxide nanoparticles | Iron | Improved nutrient assimilation | Chhipa, 2017 |
| Soybean | Nano-silica | Silicon | Stress tolerance, higher yield | Malhotra *et al.,* 2020 |

**Table 3: Nano-Pesticides in Agriculture**

| Nano-Pesticide | Target Pathogen/Pest | Mechanism | Advantage | Source |
|---|---|---|---|---|
| Silver nanoparticles | Fungal pathogens | Antimicrobial activity | Broad-spectrum control | Chhipa, 2017 |
| Silica nanoparticles | Insect pests | Physical disruption | Reduced chemical dosage | Kah *et al.,* 2013 |
| Chitosan nanoparticles | Fungal pathogens | Controlled fungicide release | Prolonged protection | Malhotra *et al.,* 2020 |
| Lipid-based nanoformulations | Various pests | Encapsulation & sustained release | Targeted delivery, less toxicity | Fraceto *et al.,* 2016 |

**4. Precision Agriculture with Nanosensors**

Nanosensors detect soil pH, nutrient levels, or early pathogen infection, transmitting data wirelessly to farmers. Real-time monitoring enables site-specific management, reducing input costs and environmental impact (Parisi *et al.,* 2015).

**5. Smart Delivery Systems**

Nanocarriers deliver fertilizers, pesticides, or growth regulators in a controlled, stimuli-responsive manner (Table 4). pH-sensitive nanocarriers release agrochemicals only under specific conditions, ensuring higher efficiency and lower risks (Fraceto *et al.,* 2016).

**Table 4: Smart Nano-Delivery Systems**

| Delivery System | Trigger | Target Application | Advantage | Source |
|---|---|---|---|---|
| pH-sensitive nanoparticles | Acidic soil/pathogen infection | Fertilizers & Pesticides | Controlled release, higher efficiency | Fraceto *et al.,* 2016 |
| Lipid-based nanocarriers | Moisture & temperature | Growth regulators | Targeted delivery, reduced wastage | Kah *et al.,* 2013 |
| Polymer-coated nanoparticles | Enzymes or soil microbes | Fertilizer | Stimuli-responsive nutrient release | Raliya *et al.,* 2016 |

**Benefits of Nano-Agriculture**

1. **Enhanced Productivity:** Improved nutrient delivery and pest management increase crop yields and quality (Raliya *et al.,* 2016).
2. **Reduced Environmental Impact:** Minimizing losses of fertilizers and pesticides reduces contamination of water and soil (Kah *et al.,* 2018).
3. **Resource Efficiency:** Precision nutrient and pesticide delivery optimizes use of water and fertilizers (Scott and Chen, 2020).
4. **Food Safety and Quality:** Lower pesticide residues and improved nutrient uptake enhance food safety and nutritional quality (Rai *et al.,* 2015).

**Recent Advances in Nano-Agriculture**

- **Nano-Fertilizers:** Nano-hydroxyapatite improves phosphorus availability and uptake (Liu & Lal, 2015).
- **Nano-Pesticides:** Chitosan nanoparticles encapsulating fungicides extend protection (Malhotra *et al.,* 2020).
- **Nanosensors:** Carbon quantum dots and nanocellulose monitor crop health (Rastogi *et al.,* 2017).
- **Carbon-Based Nanoparticles:** Graphene oxide and carbon nanotubes support nutrient delivery and stress tolerance (Zhao *et al.,* 2020).
- **Market Growth:** The global nanotechnology in agriculture market is projected to reach USD 6743.3 million by 2030, growing at a CAGR of 12.7% (Market Research Future, 2024).

**Challenges and Limitations**

1. **Safety and Regulation:** The environmental fate and toxicity of nanoparticles remain unclear (Kumar *et al.,* 2019).
2. **Scalability and Cost:** High production costs limit large-scale commercialization.
3. **Public Perception and Acceptance:** Concerns about food safety may slow adoption.
4. **Knowledge Gaps:** More research is needed on long-term impacts on soil, ecosystems, and human health (Parisi *et al.,* 2015).

**Future Prospects:**

Integration of nanotechnology with biotechnology and digital agriculture could revolutionize farming. Nano-enabled gene delivery combined with CRISPR may accelerate crop improvement. Global collaboration will be essential for developing safety protocols, fostering innovation, and ensuring equitable access to nano-agriculture.

**Conclusion:**

Nano-agriculture represents a paradigm shift in crop production and protection. By combining nanotechnology with precision agriculture, offers sustainable solutions to enhance productivity, optimize resource efficiency, and minimize environmental risks. Ongoing research and technological advancements are likely to accelerate its adoption, supporting global food security sustainably.

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# MANAGEMENT STRATEGIES OF *THRIPS PARVISPINUS* (KARNY), AN INVASIVE PEST OF INDIAN CHILLI CROP

**S. Srinivasnaik[1], V. Ratnakar*[2], K. Vijaya Lakshmi[3] and S. Malathi[1]**

[1]Department of Entomology, Agricultural College, Warangal

[2]Department of Entomology, Agricultural College, Jagtial

[3]Department of Entomology, College of Agriculture, Rajendranagar

*Corresponding author E-mail: ratnakar.ento@gmail.com

## 1. Introduction:

The first recorded mention of thrips is from the 17$^{th}$ century and a sketch was made by Philippo Bonanni, a Catholic priest, in 1691. Swedish entomologist Baron Charles De Geer described two species in the genus *Physapus* in 1744 and Linnaeus added a third species and named this group of insects as *Thrips* in 1746. In 1836, the Irish entomologist Alexander Henry Haliday described 41 species in 11 genera and proposed the order name as Thysanoptera. The first monograph on the group was published in 1895 by Heinrich Uzel who is considered the father of Thysanoptera studies. The common names for thrips include thunderflies, thunderbugs, storm flies, thunderblights, storm bugs, corn fleas, corn flies, corn lice, freckle bugs, harvest bugs and physopods (Peter, 2010). There are currently over six thousand species of thrips recognized, grouped into 777 extant and sixty fossil genera. Species of this genus are important pests causing damage directly by feeding and egg laying or indirectly by vectoring different pathogenic *tospoviruses* on economically important crops. They cause damage by rasping and sucking the sap from different parts of the plant with their well-developed left mandible. The gravid females oviposit the eggs in to the plant tissues with the help of saw-like ovipositor. Their role as pollinators has also been documented on various tropical and subtropical crops. As insect vectors, thrips are sole transmitters of *Tospoviruses* (genus: Tospovirus, family: Bunyaviridae) affecting a number of plant species belonging to unrelated plant families across the globe (NPPO-India, 2022). *Thrips* Linnaeus is the largest genus in the subfamily Thripinae with 301 species known worldwide, of which 44 are reported from India. Only three species in this genus are notorious pests as well as *tospovirus* vectors.

Biological invasion can be well regarded as a biological pollution which causes maximum losses to the biodiversity. Invasive species are threats to agricultural biodiversity as well as human and animal health. These species have great power of dispersal and adaptation. Though they are introduced unintentionally into a new area, they get a favourable climate and hence increase in number and establish well. Furthermore, the new area will be devoid of their natural enemies which unleashes the invasive species growth without any limitation.

**2. Invasion of *T. parvispinus* (Karny)**

Among the invasive alien insect species, *T. parvispinus* (Karny) is one which was first reported on *Carica papaya* L. (Caricaceae) in Bangalore in 2015 (Tyagi *et al.,* 2015) and later on *Brugmansia* sp. (Solanaceae) and *Dahlia rosea* Cav. (Asteraceae) in 2018 (Rachana *et al.,* 2018). This species is a cosmopolitan pest and has been reported from Thailand to Australia, Europe and other continents. The last two decades witnessed a drastic extension in the geographic distribution of *T. parvispinus* and it is now known to occur in France, Greece, Hawaii, Mauritius, Reunion, Spain, Tanzania and the Netherlands, besides India. Before Introduction: of this invasive thrips species, chilli thrips (*Scirtothrips dorsalis* (Hood)) commonly called as yellow thrips/native thrips in chilli ecosystem is reported to be a serious insect pest of chilli (*Capsicum annuum* L. and *Capsicum frutescens* L.) in India. It sucks the sap from the meristems of terminal leaves and buds resulting in brownish feeding scars, shrivelling, puckering, discolouration, upward curling and leaf size reduction, followed by drying and dropping of the leaf buds, whereas in fruits they cause grey to black markings, often forming a distinct ring of scarred tissue around the apex and fruit distortion (Ananthakrishnan, 1973, Reddy and Puttaswamy, 1984, Sanap and Nawale, 1987 and Ghosh *et al.,* 2009). Both nymphs and adults suck the sap from tender leaves, growing buds, flowers and young fruits by scraping surface and by piercing plant cells, which lead to upward curling of the leaves (Seal and Kumar, 2010, Moanaro and Choudhary, 2018).

**3. Nature of Damage**

Generally, it attacks the crop at all stages and cause damage to chilli leaves, flower and fruits. The infested leaves show irregular colour and streaked lines initially, later curling and deformation (Moritz *et al.,* 2013). According to Anithakumari *et al.* (2021) and Rachana *et al.* (2022), females of *T. parvispinus* mostly feed on petals and below the stamens near the ovary. Whereas, males congregate underside of leaves in large numbers and suck the sap. The infested flowers wither resulting in no fruit set. The leaf becomes deformed and fruits attain abnormal shape. The tender leaves of chilli exhibit characteristic silvery-white patches, curling, crinkling and mottling and ventral sides of older leaves show browning/bronzing with elongated petioles and later become brittle by the infestation of *T. parvispinus*. The flowers exhibit discolouration initially, later withering and dropping, while fruits are scarified/rugged by *T. parvispinus* (Nagaraju *et al.,* 2021, Basavaraj *et al.,* 2022, Lodaya *et al.,* 2022, Veeranna *et al.,* 2022, Timmanna *et al.,* 2023 and Sethy *et al.,* 2023). The damage by *T. parvispinus* in chillies results in formation of deep punctures and scratches on the underside of the leaves. As a result, the corresponding upper surface of the leaf turns yellowish, while the underside becomes reddish-brown. In case of severely infested newly emerging leaves they become dry and blighted. Flower damage results in formation of brown streaks on the petals, with distorted pollen, flower drying and withering (Plate 1 & 2) (Sireesha *et al.,* 2021, Sridhar *et al.,* 2021b, Patel *et al.,* 2022 and Seal *et al.,* 2023).

**Plate 1: Adults of female and male of *T. parvispinus (photo credit: Thrips ID.com)***

**Infested leaf buds and tender leaf terminals**

**Brick reddish coloured leaf with punctures**

**Infested flower pollen**

**Dropping of infested flower**

**Scarified pedicel of fruit** **Scarified and malformed fruits**

**Plate 2: Symptoms of damage caused by *T. parvispinus* (Karny) in leaves, flowers and fruits**

## 4. Management strategies against *Thrips parvispinus* (Karny)

Management of invasive alien insect pests has become cumbersome with the most commonly used method *i.e.* chemical control. Usage of synthetic insecticides leads to resistance, resurgence, residues and replacement of insects in any cropping system.

### 4.1 Sticky Traps

Traps are the important mechanical devices, which harbour most of the sucking pests in different cropping systems. The highest mean number of thrips *i.e. Scirtothrips aurantii* were caught on yellow sticky traps (333.50/trap) and the lowest were recorded on blue (39.50/trap) sticky traps in mango crop (Grove *et al.,* 2000). According to Sridhar and Naik (2015), the highest mean number of *S. dorsalis* were caught on blue sticky traps (19.40/trap) in chilli crop. Devi and Roy (2017) revealed that the highest mean number of thrips (4.42/sq. inch area) was caught on blue sticky traps after 7, 14, 21, 28 and 35 days after installation against *T. tabaci* in onion crop and they also observed lowest mean number of beneficial insects (0.87/trap) on blue sticky traps. According to Allan and Gillet-Kaufman (2018), the blue sticky traps were most attractive in catching *Frankliniella bispinosa* (250/trap) during flowering period in Olive crop and they also recorded less collections of predacious *Leptothrips pini*. Investigations by Kumar *et al.* (2019) revealed that the maximum number of *S. dorsalis* (19.80 adults/3 traps) were caught in blue sticky traps placed at a height of 60 cm in sweet pepper crop. According to Hossain *et al.* (2020), blue sticky traps caught the highest number of *S. dorsalis* (8.44 thrips/sq.inch area of trap) in chilli crop. Amutha (2023) stated that blue coloured sticky traps attracted highest number (102.53 thrips/trap) of *S. dorsalis* in cotton. According to her findings, the thrips catches were low at cotyledon stage (30 DAS) which gradually increased during the vegetative and flowering stage (45 to 90 DAS). Khatake *et al.* (2023) investigated the trapping efficiency of different coloured sticky traps against sucking pests of pulse crops. The findings revealed that, white trap was the most effective colour with respect to thrips catches (10.26 thrips/trap) than blue colour (9.93 thrips/trap). According to Cheema *et al.* (2024) the highest number (141.08/trap) of

*Megalurothrips distalis* were caught on blue sticky traps in mung bean crop. Irshad *et al.* (2024) stated that the maximum number of *S. dorsalis* were caught on blue coloured sticky traps (39.37±0.09 thrips/trap), when installed at 75 cm height in Gladiolus crop.

**4.2 Mulches**

Kring and Schuster (1992) stated that aluminum paint and aluminium plastic film mulches were found on par by recording lowest number of thrips of 0.40 and 0.90 per yellow dish trap, respectively in tomato which significantly reduced the *TSWV* incidence. According to Diaz-perez *et al.* (2003), the lowest per cent incidence (14.00%) of *TSWV* transmitted by thrips (*F. occidentalis*) was recorded in silver-painted mulch in tomato crop. Riley *et al.* (2012) revealed that the lowest number of thrips (36.50±3.90/ trap) and less per cent *TSWV* (31.20±2.40) were recorded in UV-reflective mulch in tomato crop. According to Razzak and Seal (2017) the lowest number (0.99±0.25) of melon thrips, *Thrips palmi* were recorded in UV reflective silver mulch in Jalapeno pepper crop. Spehia *et al.* (2017) revealed that lowest mean number of aphids (3.30/ leaf) were found in reflective silver mulch in combination with any of yellow/blue/orange traps with lowest per cent disease incidence of 3.00 per cent in bell pepper. Nasrudin *et al.* (2020) stated that the lowest number of eggs/cm$^2$ (3.47±0.50), nymphs/cm$^2$ (3.17±0.27) and adults/plant (2.24 ± 0.12) were recorded in reflective silver mulch for the management of potato whitefly in chilli crop. According to Saha *et al.* (2020) investigations, the lowest mean number (7.00-11.00/sample) of *T. palmi* were caught in UV reflective silver mulch in okra. Machanoff *et al.* (2022) revealed that, after 41 days after transplanting, the UV reflective silver mulch was found highly effective with lowest mean number of tobacco aphids, *Myzus persicae* (1.00) per plant. According to Khan *et al.* (2023), the findings revealed that, a significantly lower number of adult thrips, *T. palmi* (0.45/5 leaves) recorded in UV reflective silver on black (S/B) mulch in Tomato.

**4.3 Intercrops**

Generally, intercrops play a major role in harbouring entomophages like parasitoids and predators. These in turn reduce the population of insect pests in crops. Intercropping not only helps in reduction of pest load, but also give sustainable income to the farmers. Nampala *et al.* (1999) reported that the thrips, *Megalurothrips sjostedti* population was reduced when cowpea was intercropped with sorghum. The lowest population (42.00/20 flowers) was observed at Kumi location during 1997-1998 and 43.50/20 flowers was observed at Pallisa location during 1997-98 in cowpea crop intercropped with sorghum. Aswathanarayanareddy *et al.* (2006) stated that, the lowest number of *S. dorsalis* population (2.53/trap) was recorded in chilli+garlic intercropping system than chilli+beans (4.33/trap). According to Chikte *et al.* (2008), intercropping of cowpea in cotton was proved to be the best intercropping system in suppressing population of *T. tabaci* and *Bemisia tabaci* in cotton ecosystem. Rafee *et al.* (2013), stated that, the lowest population of *S. dorsalis* (3.10 to 3.14/ leaf) was recorded in cotton crop intercropped with cowpea. Girija *et* *al.* (2015) revealed that Groundnut + foxtail millet intercropping system was found effective with lowest mean number (2.87/terminal bud) of *T. palmi* than Groundnut+chilli intercropping system (3.93/terminal bud) after 45 days after sowing. According to Sujay and Giraddi (2015) the lowest number (0.80/leaf) of thrips, *S. dorsalis* was recorded in chilli+onion intercropping system than chilli+soybean (1.10/leaf) and chilli+groundnut (1.35/leaf). Rosulu *et al.* (2022) revealed that, the population of *Megalurothrips sjostedti* was lowest (3.84±0.11/plant) in alternate cropping (cow pea+chilli) during both wet and dry seasons in cow pea ecosystem.

**4.4 Effect of Intercropping on Population of Natural Enemies**

The adult predators and parasitoids enhance their fecundity by feeding on protein rich pollen and carbohydrate rich nectar from the flowering plants. According to Duffield and Reddy (1997) the increased activity of coccinellids and spiders was observed in chilli intercropped with leguminous crops. Idris *et al.* (1999) reported that the number of coccinellid eggs and adults, chrysopid larvae and adults and spiders were significantly higher in chilli+maize intercropping system as compared to chilli+peanut and chilli alone. Srinivasarao *et al.* (2012) revealed that castor with leguminous crops like castor+cluster bean, castor+cowpea, castor+black gram, castor+green gram and castor+groundnut had significantly higher populations of coccinellids than other intercropping systems, with mean number of population ranging from 0.38 to 0.48 per plant. Similarly, the spider population (0.27 to 0.411/plant) was also higher in castor intercropped with leguminous crops. Manjula and Lakshmi (2014) revealed that highest population of coccinellids and spiders were recorded in ground nut+cow pea intercropping system with 2.44/plant and 1.32/plant respectively. Among the coccinellids, *Chelomenes sexmaculata* was the predominant species (70.00%) and spiders belong to Lycosidae were predominat. According to Sujay and Giraddi (2015), chilli intercropped with coriander and onion supported good activity of the predators *viz.,* coccinellid beetles (*Menochilus sexmaculatus)* (1.81/plant and 1.71/plant) and chrysopids, *Chrysoperla zastrowi sillemi* (2.25/plant and 2.19/plant) than chilli + soybean (1.62/plant and 1.88/plant) and chilli + groundnut intercropping systems (1.56/plant and 1.85/plant). Girija (2015) revealed that highest population of coccinellids and predatory spiders were recorded in groundnut+foxtail millet (1.07/plant, 1.53/plant) followed by groundnut+bajra (0.87/plant, 0.93/plant) and groundnut+sorghum (0.53/plant, 0.87/ plant) intercropping systems. According to Baloch *et al.* (2016), chilli+pea cropping system had the highest mean population of spiders (0.18±0.02), green lacewings (0.10±0.01) and ladybird beetles (0.36±0.01). Swaroopa *et al.* (2018) revealed that the highest mean population of coccinellids and spiders was observed in groundnut+cowpea intercropping in 3:1 ratio (1.64, 1.65 coccinellids/plant and 1.48, 1.83 spiders/plant, respectively) followed by 7:1 ratio (1.20, 1.62 coccinellids/plant and 1.34 and 1.38 spiders/plant, respectively).

**4.5 Chemical Control**

Aristizabal *et al.* (2016) assessed different biorational and synthetic insecticides against *S. dorsalis* in chilli crop and found spinosad 45SC at 0.63 ml $l^{-1}$ to be superior which resulted in highest per cent reduction over control (97.00 - 99.00%), followed by *Metarhizium brunneum* ($5.5x10^{12}$) at 2.5 ml $l^{-1}$ (71.00-72.00%), azadirachtin at 0.6 ml $l^{-1}$ (61.00-67.00%), horticultural oil at 10 ml $l^{-1}$(48.00-59.00%) and the lowest reduction with *Beauveria bassiana* (2.1 X $10^{13}$) at 2.5 ml $l^{-1}$ (47.00-55.00%). According to Sathua *et al.* (2017), efficacy of different insecticides and botanicals against *S. dorsalis* in chilli revealed that imidacloprid 17.8SL at 20 g a.i. $ha^{-1}$ caused maximum reduction in thrips population (82.46%), followed by acephate 75SP at 350 g a.i. $ha^{-1}$(80.86%) and among the botanicals, NSKE 5% at 5 g a.i. $ha^{-1}$ caused maximum mortality of 64.50 per cent, while garlic and onion extract showed comparatively less performance with 55.98 per cent and 51.53 per cent respectively. Among all the treatments, the highest yield (2.28 t/ha) and B:C ratio (1:16.66) was found in imidacloprid 17.8SL treatment. Kurbett *et al.* (2018) evaluated different IPM modules against *S. dorsalis* in chilli crop. The findings revealed that the module which included root dip with imidacloprid 17.8SL at 0.5 ml $l^{-1}$ for 30 min. at the time of transplanting + acetamiprid 20SP at 0.2 g $l^{-1}$+ fenpropathrin 30EC at 0.5 ml $l^{-1}$ + diafenthiuron 50WP at 1.0 g $l^{-1}$ + spiromesifen 240SC at 1 ml $l^{-1}$ + spinosad 45 SC at 0.2 ml $l^{-1}$ + rynaxypyr 18.5 SC at 0.2 ml $l^{-1}$ was found most effective in reducing the thrips population (0.71/leaf) with highest dry chilli yield (11.84 q/ha) and B:C ratio of 3.29 over the other modules which included bio pesticides, botanicals and trap crops. According to Manjunatha *et al.* (2018), the application of spinosad at 0.025% a.i. resulted in maximum reduction of *S. dorsalis* (91.00%) in chilli with highest green chilli yield (9.51 t/ha) and B:C ratio of 2.29, followed by acephate at 0.15% a.i. (72.00%), dimethoate at 0.17% a.i. (69.00%), imidacloprid at 0.05% a.i. (61.00%) and the least was recorded in fipronil at 0.2% a.i. (61.00%). Latha and Hunumanthraya (2018) tested different modules against *S. dorsalis* in chilli. Among all the modules, the chemical module (imidacloprid 17.8SL at 0.3 ml $l^{-1}$ l + chlorantraniliprole 18.5SC at 0.25 ml $l^{-1}$, flubendiamide 48SC at 0.2 ml $l^{-1}$, spiromesifin 30SC at 2 ml $l^{-1}$ and spinosad 45SC at 0.25 ml $l^{-1}$) was highly effective and resulted in highest yield (12.8 t/ha), B:C ratio of 1:2.90 than bio-intensive and recommended plant protection modules. The findings made by Sruthi *et al.* (2018) on evaluation of different IPM modules against sucking pests of capsicum revealed that bio intensive module which included neem cake + vermicompost application at 50 g per plant + root dip with imidacloprid 17.8SL at 0.5 ml $l^{-1}$ + three sprays of azadirachtin 10000 ppm at 1.0 ml $l^{-1}$ + *Lecanicillium lecanii* at 5.0 g $l^{-1}$ + spraying of *Pseudomonas fluorescens* at 5.0 g $l^{-1}$ + chilli-garlic extract at 0.5 per cent + cyantraniliprole 10.26 OD at 1.5 ml $l^{-1}$ and two sprays of ecomite at 3.0 ml $l^{-1}$ was quite effective against capsicum sucking pests and resulted in highest yield (54.53t/ha) and B:C ratio (2.97) over other modules which comprised only botanicals and insecticides. Sreeninvas *et al.* (2019) tested the efficacy of imidacloprid 60 FS (10, 20 ml $kg^{-1}$ seed) and thiamethoxam 35 FS

(15, 30 ml kg$^{-1}$ seed) against *S. dorsalis* in chilli. The results revealed that imidacloprid 60 FS at 20 ml kg$^{-1}$ seed registered minimum thrips population of 4.42 and 2.87 per leaf from MARS, Raichur and ARS, Bidar respectively, hence it could harvest highest fruit yield of 24.60 and 23.95 q ha$^{-1}$ with a B:C ratio of 2.20 and 2.14, respectively. However, this treatment showed non-significant difference with thiamethoxam 35 FS at higher dosage of 30 ml kg$^{-1}$ seed which registered 3.96 and 1.44 thrips per leaf from MARS, Raichur and ARS, Bidar respectively. The fruit yield obtained from these two treatments were 26.35 and 25.60 q ha$^{-1}$ with a B: C ratio of 2.36 and 2.29. Mishra *et al.* (2022) assessed the efficacy of different novel and conventional insecticides against *S. dorsalis* in chilli and reported that fipronil 80WG and spiromesifen 22.9SC were found superior (0.98 and 1.04 thrips/leaf, respectively) and resulted in 75.60 and 74.10 per cent reduction over untreated control, respectively, while spiromesifen 22.9SC showed maximum reduction in leaf curl and fruit damage (84.60 and 83.10%, respectively) with maximum chlorophyll content in leaves and green chilli yield (93.85 q ha$^{-1}$). Nagaraju and Ashwanikumar (2022) stated that fipronil 5SC (94.06%) was proved to be the most effective treatment against *S. dorsalis* in chilli followed by spinosad 45SC (93.16%), imidacloprid 17.8SL (92.27%), whereas neem oil 1500 ppm (60.69%) was found to be least effective against *S. dorsalis.* Among the chemical treatments, fipronil 5SC (94.06%) was recorded highest yield (87.9 q/ha) and B:C ratio of 1:11.36 in chilli crop. According to Priya *et al.* (2022), the module which consisted of foliar spraying of fipronil 80WG at 0.2 g l$^{-1}$, followed by spinetoram 11.7SC at 1 ml l$^{-1}$, spirotetramat 240 SC at 0.8 ml l$^{-1}$, acetamiprid 20SP at 0.2 g l$^{-1}$, thiamethoxam 25WG at 0.2 g l$^{-1}$ and dimethoate 30EC at 2 ml l$^{-1}$ was found most effective with the lowest mean population of *T. parvispinus* (14.72/leaf) and 87.08 per cent increase over untreated control with highest yield (30.55 q/ha) and B:C ratio of 1:2.80 in chilli crop than other modules which included botanicals and bio rational pesticides. Manideep *et al.* (2023) reported that spinosad 45SC at 0.2 ml/l reduced the thrips, *T. parvispinus* incidence significantly with mean per cent reduction of 80.20 followed by spinetoram 11.7SC at 0.25 ml l$^{-1}$ (76.245%), cyantraniliprole 10OD at 1 ml l$^{-1}$ (73.92%) and fipronil 5SC at 1 ml l$^{-1}$ (72.24%), while in biorationals, pongamia soap @ 5 g l$^{-1}$reduced the thrips population significantly with 74.90 mean per cent reduction over control followed by neem soap at 5 g l$^{-1}$ (72.25%), azadirachtin 10000 ppm at 2 ml l$^{-1}$ (71.10%), *Beauveria bassiana* (1X10$^{8}$) at 10 g l$^{-1}$ (66.76%), *Isaria fumosorosea* (1X10$^{8}$) at 5 g l$^{-1}$ (64.93%), *Lecanicillium lecanii* (1x10$^{8}$) at 10 g l$^{-1}$ (63.72%) and *Metarhizium anisopliae* (1X10$^{8}$) at 10 g l$^{-1}$ (62.46%) in chrysanthemum crop. Poornima *et al.* (2023) evaluated different synthetic insecticides against *S. dorsalis*. The results revealed that spinetoram 11.7SC at 60 g a.i. ha$^{-1}$ was observed to be superior in managing chilli thrips *i.e. S. dorsalis* with a per cent population reduction of 93.35 and the lowest thrips population (0.53/3 leaves), followed by cyantraniliprole 10.26 OD at 60 g a.i. ha$^{-1}$ (0.73/3 leaves, 90.78%), spirotetramat 15.31 OD at 60 g a.i. ha$^{-1}$ (1.10/3 leaves, 85.44%) and fipronil 5SC at 50 g a.i. ha$^{-1}$ (1.67/3 leaves, 76.49%). Muralimohan *et al.* (2023) studied efficacy of different insecticides and biorational pesticides against *T. parvispinus* in chilli. The findings revealed that broflanilide 30SC (18.60 g a.i/ha) and fluxametamide 10EC (40 g a.i./ha) were found highly effective in reducing *T. parvispinus* population in chilli with 91.44 per cent and 87.84 per cent population reduction respectively, followed by spinetoram 11.7 SC (60 g a.i./ha) (83.60%), tolfenpyrad 15 EC (150 g a.i./ha) (79.49%), spinosad 45 SC (73.00 g a.i. $ha^{-1}$) (78.31%), cyantraniliprole 10.26 OD (60 g a.i./ha) (75.57%) and thiamethoxam 25 WG (37.50 g a.i./ha) (72.86%). The biorationals *viz., Lecanicillium lecanii* (2.50 kg/ha), *Beauveria bassiana* (2.50 kg/ha) and azadirachtin 1.00% (2 ml/l) recorded comparatively higher thrips populations with 41.97, 38.98 and 40.06 per cent population reduction, respectively. According to Sambaiah *et al.* (2023), spirotetramat (160 g/acre) was found most effective and recorded lowest *T. parvispinus* population in chilli at 3 days (4.30/flower) and 5 days after spraying (5.12/flower) and showed highest population reduction over control (72.70%, 66.59%) with highest dry chilli yield (58.60 q $ha^{-1}$) and ICBR (3.58) followed by fipronil 80WG (25 g/acre)with population count (5.00/flower, 5.27/flower) and per cent reduction over control (70.59% and 52.22%), spinotoram 11.70SC with population count (5.35/flower, 5.80/flower) and per cent reduction over control (52.71% and 50.75%). Seal *et al.* (2023) assessed the efficacy of different insecticides against *T. parvispinus* in finger hot pepper. The findings revealed that novaluron 10 EC at 360 ml $acre^{-1}$ was found most effective insecticide and recorded lowest thrips population (0.70/leaf), followed by tolfenpyrad 15EC at 630 ml $acre^{-1}$ (1.10/leaf), spinetoram 11.7SC at 240 ml $acre^{-1}$ (2.10/leaf) and mythomyl 29LV at 1080 ml $acre^{-1}$ (2.20/leaf). According to Raut and Aswanikumar (2024), among the insecticides evaluated, imidacloprid 17.8SL at 1 ml $l^{-1}$ (0.47 thrips/3 leaves) was proved to be most effective treatment against *S. dorsalis* in chilli, followed by spinosad 45SC 0.3 ml $l^{-1}$ (0.68 thrips/3 leaves), fipronil 5SC at 2 ml $l^{-1}$ (1.25 thrips/3 leaves) and azadirachtin 10000ppm3 ml $l^{-1}$ (2.26 thrips/3 leaves). Among the treatments studied, the most economical treatment imidacloprid 17.8SL recorded highest yield (130 q/ha) cost benefit ratio (1:10.65) followed by spinosad 45SC (118 q/ha, 1:10.35), fipronil (100 q/ha, 1:8.19) and the lowest with azadirachtin 10000 ppm (75q/ha, 1:6.13). Devare *et al.* (2025) assessed the efficacy of different insecticide spray schedules against chilli thrips, *S. dorsalis*. The findings revealed that first spray schedule (fipronil 0.5SC + tolfenpyrad 15EC + cyantraniliprole 10.50 OD) was found most effective in reducing the thrips population (1.25/leaf) and it was at par with second spray schedule (lambda-cyhalothrin 5 SC + diafenthiuron 50 WP + emamectin benzoate 0.5 SG followed by spinosad 45 SC + broflanilide 300G/L SC + flubendamide 20 WG) (1.95/leaf).

**5. Future Strategies**

Development of resistant hybrids against *T. parvispinus* is the first line of defence which needs to be taken up. *T. parvispinus* is a polyphagous pest, life table studies on different host plants is needed to know the biology and its demographic statistics. It is distributed in different agro ecosystems across the globe. Hence, morphological and molecular characterization and genetic variation analysis is needed for development of effective management strategies. Development of location specific IPM module is needed by including all the eco-friendly pest management components. Strengthening of quarantine measures is needed for the movement of vegetative propagation material. Virus vector relationships of *T. parvispinus* is needed to be studied for any transmission of *TSV* in different host plants. Networking projects need to be formulated for effective management involving Agricultural/Horticultural and allied institutions at the national and international level.

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# PHYSIOLOGICAL PRINCIPLES OF DRYLAND CROP PRODUCTION: MECHANISMS, MANAGEMENT AND RECENT ADVANCES

**Geeta Kalaghatagi*, Basavaraj S Yenagi,**
**Sajjan. G, T H V Meghana and Sneha Sangappa Benal**
Department of Agronomy, University of Agricultural Sciences, Dharwad
*Corresponding author E-mail: geetakalaghatagiedu@gmail.com

**Abstract:**

Dryland agriculture faces growing challenges from variable precipitation, rising evaporative demand, and more frequent heat/drought episodes. A physiology- centred view links mechanisms - water capture, stomatal regulation, carbon assimilation, phenology, and nutrient-water interactions - to management and breeding options that improve yield stability per unit of available water. This review synthesizes core physiological principles relevant to dryland cropping, examines management practices that alter crop physiology (conservation agriculture, mulching, rotations, targeted irrigation, bio stimulants) and surveys recent advances in trait-based breeding, crop modelling and remote sensing that help scale physiology to landscapes. We highlight the "effective use of water" (EUW) framing as a practical bridge between plant physiology and farm outcomes, summarize recent field evidence for key interventions and identify priority knowledge gaps and research directions for resilient dryland systems. Key citations are given to recent open-access reviews and meta-analyses (2022–2024) that underpin the main claims Rane *et al.* (2022).

**Introduction:**

Dryland agriculture - defined here as cropping systems that rely primarily on precipitation rather than irrigation - covers a large fraction of global croplands and supports millions of smallholders and large commercial farms alike. Dryland systems are characterized by limited and highly variable rainfall, high potential evapotranspiration (PET) and soils that often have limited water-holding capacity and organic matter. Because water availability is both low and temporally unpredictable, crop performance depends on how plants capture water, allocate carbon, regulate water loss and time their development relative to rainfall and seasonal stresses. A physiology-centred review is useful because it connects *mechanisms* (what plants do) to *levers* (what managers and breeders can change) and thereby points to integrated, scalable solutions for yield stability and resource-use efficiency.

This review first summarizes the core physiological principles that determine crop performance in drylands. It then links those principles to management practices and breeding strategies, examines tools for scaling physiology (models, remote sensing, phenomics), and finally highlights recent advances and remaining gaps for research and extension.

## 2. Core Physiological Principles

### 2.1 Soil-Root Capture of Water

The first limitation in drylands is supply: how much water the soil stores and how effectively roots access it. Root system architecture (depth, angle, branching and hydraulic conductance) determines the temporal and spatial pattern of water uptake; deep or steep-rooting genotypes can access subsoil moisture late in the season, while shallow, dense root systems may capture short, frequent rains more effectively. Soil texture and structure control water infiltration and retention; higher organic matter increases available water capacity and improves aggregate stability, favouring deeper wetting fronts and longer water availability between rains. Processes such as hydraulic redistribution (roots moving water between soil layers) can buffer shallow-rooted plants during dry spells but are context-dependent. Recent syntheses emphasize rooting traits as central to dryland performance but also caution that root traits interact with management and soil constraints, making simple trait-yield rules elusive. Rane *et al.* (2022).

### 2.2 Stomatal Regulation and Whole-Plant Water Use

Stomata are the gatekeepers for water loss and $CO_2$ gain. Plants exhibit a continuum from isohydric behaviour (tight stomatal control, conservative water use) to anisohydric behaviour (more open stomata under stress, risking hydraulic failure but sustaining photosynthesis). These strategies produce trade-offs: conservative stomatal behaviour can protect plants from severe water deficits but may limit carbon gain and yield when water stress is moderate or when timely rainfall follows a dry spell. The concept of *effective use of water* (EUW) reframes goals from instantaneous water-use efficiency (WUE) to cumulative, season-long outcomes: the aim is to maximize crop biomass and harvestable yield per unit of *available* water by optimizing uptake timing, stomatal behaviour and carbon partitioning. Reviews in the last few years provide a clear rationale for EUW as the operational target for dryland systems. Rane *et al.* (2022) and Vadez (2023).

### 2.3 Photosynthesis, Carbon Allocation and Recovery

Drought reduces photosynthetic capacity by both stomatal limitation (reduced $CO_2$ entry) and non-stomatal damages (photoinhibition, metabolic constraints). The ability of a crop to maintain or rapidly recover photosynthetic activity after stress episodes - and to remobilize stored carbohydrates to grain - is a key determinant of final yield in many dryland crops. "Stay-green" traits that sustain green leaf area and active photosynthesis during grain filling have shown value in some cereals under terminal drought, by supporting grain filling when late-season water is scarce.

### 2.4 Phenology: Escape and Matching to Rainfall

Phenology (duration and timing of developmental phases) provides a powerful, low-cost lever in drylands. Early-maturing cultivars can "escape" terminal drought by completing grain fill before late-season moisture deficits; conversely, longer-duration cultivars that better exploit stored soil moisture can yield more when seasonal rains are adequate. Matching cultivar phenology to local rainfall patterns and adjusting sowing dates are among the most reliable adaptation strategies available to farmers.

### 2.5 Nutrient-Water Interactions and Co-Stressors

Water availability strongly influences nutrient uptake and soil biogeochemical processes; drought lowers diffusion and mass flow of nutrients towards roots and can limit N uptake and use efficiency. Salinity and heat often co-occur in drylands and compound physiological stress. Integrated management that maintains or increases soil organic matter and reduces salinization risk supports both water and nutrient capture.

## 3. Management Practices that Modify Crop Physiology

This section links practical interventions to physiological mechanisms and summarizes recent evidence for effectiveness in dryland settings.

### 3.1 Conservation Agriculture (Reduced Tillage, Residue Retention)

Conservation agriculture (CA) - minimal soil disturbance, residue retention and crop rotation - alters the crop microenvironment and soil structure in ways that matter physiologically: residues reduce direct soil evaporation and moderate surface temperature, no-till preserves soil structure and macro-porosity for infiltration and increasing organic matter improves available water capacity and microbial-driven nutrient cycling. Recent large-scale syntheses indicate CA can improve soil health metrics substantially and support yields under warming and variable rainfall in many systems, although benefits accrue over multi-year timescales and depend on local context and management integration. Thus CA is a system-level strategy to increase the *effective* soil water available to crops and to buffer against interannual variability. Teng *et al.* (2024) Dash *et al.* (2025).

### 3.2 Mulching and Surface Covers

Surface mulches (crop residues, straw, or synthetic films) reduce soil evaporation, moderate soil temperature, lower erosion, and suppress weeds — all of which conserve available water for crop uptake, especially during establishment and early growth. Recent reviews and field studies in dryland contexts report consistent moisture-conserving benefits and yield increases where mulching is feasible, though practical constraints (residue availability, labour, cost) affect adoption. Mulches also influence soil microbial activity and nutrient cycling, with implications for rooting and nutrient uptake Demo *et al.* (2024).

### 3.3 Crop Rotations, Cover Crops and Diversification

Diverse rotations that include legumes can increase soil nitrogen, improve structure and boost residue inputs - indirectly improving water infiltration and plant-available water. Cover crops can protect the soil and build organic matter, but in strictly water-limited drylands they must be timed or terminated to avoid pre-season water competition. Evidence shows rotation benefits are system-specific; when well-managed, rotations increase resilience, but they are not a universal cure and require local adaptation.

### 3.4 Targeted Water Management: Deficit and Supplemental Irrigation

Where limited supplemental water is available, deficit irrigation strategies (regulated deficit irrigation or supplemental late-season watering) can be used to optimize EUW by applying water at the most yield-critical stages (e.g., flowering and grain filling in many cereals). Such targeted watering demands phenological matching and monitoring to be effective. In many smallholder dryland systems, low-cost moisture-conserving practices (mulch, residue retention) are higher priority where irrigation is unavailable.

### 3.5 Biostimulants, Soil Amendments and Microbiome Interventions

Biostimulants (seaweed extracts, humic substances, microbial inoculants) are widely promoted to improve stress tolerance and root growth. Meta-analyses find variable average yield benefits across environments; effectiveness is highly context-dependent and often modest in large-field trials. While some biostimulants show promise under specific conditions, the evidence base calls for cautious, locally validated use and better mechanistic linking to physiological responses (e.g., osmotic adjustment, root growth stimulation) Li *et al.* (2022).

## 4. Breeding and Trait-Based Approaches

Breeding for dryland performance increasingly focuses on physiological traits that translate to improved EUW and yield stability rather than single “drought genes.” Key target traits include:

- Root architecture (depth, angle, hydraulic conductance) for deeper or more timely water capture.
- Controlled transpiration or “limited-transpiration” traits that save water early to enable grain fill later.
- Stay-green and efficient remobilization of carbohydrates to grain.
- Improved recovery after transient stress episodes.

Recent reviews emphasize that while molecular advances (gene editing, candidate genes for osmotic adjustment, ABA signalling, ROS regulation) provide tools, the bottleneck remains robust field-level validation across variable environments. Translational gaps persist because controlled-environment trait performance often fails to scale to complex rainfed field conditions. Trait combinations (ideotypes) adapted to specific rainfall regimes, together with highthroughput field phenotyping, offer the best path forward Hagpanah *et al.* (2024) and Rane *et al.* (2022).

**5. Tools That Link Physiology to Management: Modelling and Remote Sensing**

Scaling physiological understanding from plots to landscapes requires models and observations that capture G×E×M (genotype × environment × management) interactions. Crop models (CERES, Aqua Crop, APSIM and others) simulate water balances, phenology and yield responses to management and genotype choices and are increasingly coupled to remote sensing for calibration and spatial upscaling.

Remote sensing (satellite and UAV) provides repeated observations of canopy status (NDVI, solar-induced fluorescence, canopy temperature) that can serve as proxies for biomass, photosynthetic activity and stress. Data assimilation frameworks that combine remote sensing and crop models improve regional yield forecasts and help identify pockets of vulnerability or success; recent work has advanced methods to assimilate canopy properties and soil moisture proxies into models to improve predictions. These tools also support decision-support systems for sowing date optimization and targeted management at farm or landscape scale Wang *et al.* (2024) and Mogbhel *et al.* (2025).

**6. Recent Advances and Knowledge Gaps**

**6.1 Recent Advances**

- **Effective Use of Water (EUW)**: The EUW framework has gained traction as a more operationable target than instantaneous WUE, emphasizing whole-season allocation and timing to improve yield per unit of available water. This reframing connects breeding, physiology and management toward the same metric Rane *et al.* (2022).
- **Conservation Agriculture Benefits**: Large-scale syntheses and multi-year trials report improved soil health and resilience under CA, with notable gains in soil organic matter, microbial biomass and sometimes stabilized yields under warming scenarios - benefits that typically accrue over years rather than immediately Teng *et al.* (2024).
- **Mulching Evidence**: Recent reviews consolidate evidence that mulching conserves soil moisture and can improve establishment and yields in many dryland contexts when residue inputs are available Demo *et al.* (2024).
- **Integrating Remote Sensing and Models**: Methodological advances in data assimilation and automated model calibration are improving the ability to scale physiological insights across regions for decision support Wang *et al.* (2024) and Mogbhel *et al.* (2025).

**6.2 Knowledge Gaps and Challenges**

- **Trait-To-Yield Translation**: Many promising physiological traits show limited or inconsistent yield benefits across heterogeneous dryland environments. Multi-environment field validation and ideotype-based breeding remain priorities Haghpanah *et al.* (2024).

- **Socio-Economic and Adoption Barriers**: Agronomic interventions (residue retention, mulching, rotations) face labour, residue-availability and market-barrier constraints that influence farmer uptake; social research is critical to tailor packages to local realities.
- **Biostimulant Evidence Base**: While meta-analyses report some average yield gains, effects vary widely by crop, product and environment; robust, independent field trials under dryland conditions are still needed Li *et al.* (2022).
- **Scaling Uncertainty**: Model and remote-sensing based tools are improving, but uncertainties in soil inputs, management records and sub-field variability limit predictive skill in many regions. Investments in ground truthing, local data collection and participatory validation would improve trust and utility Wang *et al.* (2024).

**Practical Recommendations for Farmers and Researchers**

For farmers or extension

1. **Match Phenology to Local Rainfall**: prioritize cultivar choice and sowing date to align growth stages with expected rainfall patterns; phenology matching is often the most reliable adaptation.
2. **Retain Residues Where Feasible**: residue retention and minimal tillage conserve early-season moisture and build soil health - adopt incrementally if residue availability or livestock feed trade-offs exist Teng *et al.* (2024).
3. **Use Mulches for Establishment**: if residues or affordable mulches are available, use them to improve stand establishment and reduce evaporation losses Demo *et al.* (2024).
4. **Test Inputs Locally**: pilot any biostimulant or novel amendment on a small scale before wide adoption; responses are highly context-specific Li *et al.* (2024).
5. **For Researchers and Policy-Makers**

- **Prioritize Multi-Year, Multi-Site Field Validation** of physiological traits and agronomic packages to understand their stability across heterogeneous dryland environments Haghpanah *et al.* (2024).

1. **Invest in Data Systems**: improve soil maps, local weather records, and cost-effective soil moisture monitoring to support model calibration and farmer advisory systems. Wang *et al.* (2024)
2. **Integrate Socio-Economic Research** into technology development to address adoption constraints (labour, residue trade-offs, input costs).
3. **Advance Decision-Support Tools** that combine remote sensing, phenology forecasts and simple user interfaces for farmers and extension agents.

**Conclusion:**

Dryland crop production is a systems challenge that requires connecting plant physiology, sensible management and tools for scaling and decision-making. The EUW framing - maximizing yield per unit of *available* water - provides a practical target that unites breeders, physiologists and agronomists. Evidence accumulated in the last few years strengthens the case for conservation agriculture and mulching as water-conserving practices, highlights the promise and limits of biostimulants, and demonstrates that model-remote sensing integration can improve regional decision-making. Major needs remain: robust trait-to-yield validation across environments, locally appropriate packages that address socio-economic constraints, and improved data and decision tools that scale physiological insights to the farm and landscape levels. Addressing these priorities will increase resilience and productivity of dryland systems in a changing climate.

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# FROM POLLINATION TO PROTECTION: THE EMERGING ROLE OF ENTOMOVECTORING IN SUSTAINABLE CROP HEALTH

**Gurveen Kaur, Hitendra Kumar*, Ravindra Kumar and Vaibhav Saini**

School of Agricultural Sciences,

Shri Guru Ram Rai University, Dehradun-248001, Uttarakhand, India

*Corresponding author E-mail: hitendrakumar@sgrru.ac.in

**Abstract:**

Entomovectoring is an innovative and sustainable approach in crop protection that utilizes insects, primarily pollinators such as honey bees and bumblebees, to deliver beneficial microbial agents directly to plants. This strategy integrates disease management with pollination services, offering dual benefits of enhanced crop yield and quality alongside eco-friendly pest control. Over the past four decades, research has demonstrated the successful application of fungal and bacterial biocontrol agents against various plant pathogens in both field and greenhouse conditions. The chapter discusses the historical development, mechanisms of microbial acquisition and deposition by insect vectors, selection of suitable insects and microbial agents, and practical applications in horticultural and field crops. Challenges related to ecological, technical, and economic constraints are addressed, along with integration into Integrated Pest Management (IPM) frameworks. Future prospects include advances in microbial formulations, precision agriculture, and commercialization strategies to enhance efficacy and adoption. Entomovectoring thus represents a promising, climate-smart tool for sustainable agriculture and eco-friendly crop protection.

**Keywords:** Entomovectoring, Crop Protection, Biocontrol Agents, Pollinators, Integrated Pest Management (IPM), Sustainable Agriculture, Microbial Formulations.

**Introduction:**

Entomovectoring is a biological crop protection technique that uses pollinators, such as bees, as vectors to deliver microbial control agents (bacteria or fungi) directly to crops, offering pollination and pest/disease management simultaneously. This sustainable approach integrates natural processes, making it more eco-friendly than traditional methods. Protecting beneficial arthropods is crucial as they provide multiple ecosystem services, including pollination, pest control, resilience, and productivity. Managed bees like bumblebees, mason bees, and honey bees can disseminate biocontrol agents to flowering crops, enhancing yields through combined pollination and crop protection.

Pollinator foraging is density dependent, and conspicuous plant species can increase visitation to neighbours but may also compete for pollination at high densities. Commercial use of pollinators and microbial agents is expanding, with inoculation systems like hive dispensers enabling bees to spread beneficial microbes. Selecting suitable vector species and locally adapted pollinators improves system efficiency but requires further regional research.

Over the last 25 years, entomovectoring has been tested against pathogens like *Botrytis cinerea* (grey mold) in strawberries, raspberries, and blueberries, as well as insect pests such as thrips and tarnished plant bug in tomato and pepper. Case studies show bumblebees can disperse *Beauveriabassiana* effectively, suppressing thrips with minimal impact on bee populations. Similarly, novel formulations such as spray-dried *Lactiplantibacillusplantarum* have shown potential in strawberry crops, though protection results remain inconsistent.

**Scope of Entomovectoring**

The scope of entomovectoring in crop protection is broad, extending well beyond the simple delivery of beneficial microbes. It offers a dual advantage by combining pollination with biological control, where insect vectors simultaneously enhance crop yield through pollination and suppress diseases by depositing antagonistic microorganisms on flowers and other susceptible plant parts. This technology provides a sustainable alternative to chemical pesticides, reducing environmental contamination, safeguarding human and pollinator health, and aligning with the goals of eco-friendly agriculture. Entomovectoring has shown particular promise in greenhouse crops such as tomato, strawberry, cucumber, and pepper, but its potential extends to open-field crops, fruit orchards, floriculture, and even seed production systems. Furthermore, it can be effectively integrated into Integrated Pest Management (IPM) programs, complementing cultural, mechanical, and biological methods while supporting reduced pesticide use. With ongoing advancements in microbial formulations, nanotechnology-based carriers, and precision agriculture tools, entomovectoring is poised to become a vital component of climate-smart farming systems. Its scope also encompasses commercial opportunities, innovative research directions, and the development of resilient strategies for sustainable crop protection in the face of growing agricultural challenges.

**Historical Development**

The concept of entomovectoring emerged in the late 20th century, when researchers began exploring the natural movement of pollinators as a means of carrying microbial agents to plants. Early studies in the 1980s and 1990s demonstrated that bees could successfully transfer fungal antagonists such as *Trichoderma* and *Clonostachys* to flowers for the suppression of grey mould (*Botrytis cinerea*) in crops like strawberry and tomato. These pioneering efforts established the foundation for integrating pollinators into crop protection strategies. With the development of hive-based dispenser systems, where foraging insects pick up powdered formulations of beneficial microbes before leaving the hive, entomovectoring became a practical tool that could be tested under both greenhouse and field conditions.

**How Insects Act as Vectors of Beneficial Agents**

Insects, particularly pollinators, are highly effective natural vectors because of their foraging behavior, frequent movement between plants, and intimate contact with floral structures. The process of entomovectoring begins when insects pass through a dispenser system placed at the entrance of a hive or release station. This device contains a formulation of beneficial microorganisms,commonly fungal antagonists, bacterial biocontrol strains, or plant growth-promoting agents,in a fine powder or granule form. As the insects exit the dispenser, the particles adhere to their body surfaces, including hairs, legs, and mouthparts, without interfering with flight or pollination efficiency.

Once in the crop field, the insects visit flowers in search of nectar and pollen. During this activity, they transfer the microbial inoculum to floral organs such as petals, anthers, and stigmas, which are also the primary infection courts for many plant pathogens. The beneficial microbes then colonize these surfaces, where they can outcompete pathogens, produce antimicrobial compounds, parasitize fungal structures, or trigger plant defense responses.

The efficiency of insects as vectors is enhanced by several biological traits. Their high frequency of floral visitation increases the number of inoculum deposition events, while their fidelity to specific crops during bloom ensures that the beneficial agents are consistently targeted to the host plant. Additionally, their ability to forage over large areas allows for wide distribution of the agents, often more uniform than that achieved by conventional spraying. This natural behavior makes insects not only effective pollinators but also reliable carriers of microbial protectants, thereby combining two essential ecosystem services—pollination and plant protection—into a single process.

**Process of Microbial Acquisition and Deposition on Flowers/Plants**

The process of microbial delivery through entomovectoring involves a sequential interaction between insects, microbial inoculum, and crop flowers. It begins when pollinators such as honey bees or bumblebees exit their nests or hives through specially designed dispenser systems containing formulations of beneficial microorganisms, typically in dry powder, dust, or granular carriers compatible with insect physiology. As insects pass through the dispenser, particles of inoculum adhere to the dense setae on their bodies, as well as to legs, antennae, and mouthparts, in a passive acquisition phase that does not disrupt their flight or pollination. During subsequent foraging, deposition occurs as the inoculum is dislodged onto floral surfaces such as petals, anthers, and stigmas,key sites for pathogen invasion. For instance, *Bombusterrestris* visiting strawberry flowers can deposit *Clonostachysrosea* spores onto stigmas, suppressing *Botrytis cinerea*, while honey bees vectoring *Trichoderma harzianum* to tomato flowers enable colonization of infection courts and prevention of fungal establishment. The effectiveness of this deposition depends on inoculum density, frequency and duration of floral visits, and compatibility of the microbial agent with the floral microenvironment. Once transferred, beneficial microbes germinate and colonize floral tissues, forming protective barriers that compete with, parasitize, or inhibit pathogens, and in some cases induce systemic resistance in plants. Thus, through its two-step acquisition and deposition process, entomovectoring provides a precise, repeated, and biologically efficient method of delivering protective agents directly to infection-prone sites, serving as an eco-friendly alternative to conventional spraying.

**Insect Vectors in Entomovectoring**

The success of entomovectoring largely depends on the insect species employed as carriers of beneficial microorganisms. Ideal vectors must exhibit frequent and consistent floral visitation, possess hairy or setose body surfaces that facilitate inoculum adherence, and display strong fidelity to the target crop during its flowering period. Among the diverse groups of insects, bees have emerged as the most effective and widely used vectors due to their biology, behavior, and co-evolutionary relationship with flowering plants.

**Honey bees (***Apismellifera***)** are the most extensively studied insect vectors because of their wide availability, well-developed colony management systems, and efficiency in pollination. They have been successfully used to deliver *Trichoderma harzianum* and other antagonists in crops such as tomato, cucumber, and apple. However, their large foraging ranges and tendency to visit multiple plant species can sometimes dilute their effectiveness for precise microbial delivery.

**Bumblebees (***Bombus*spp.**)** are particularly important in greenhouse and protected cropping systems. Species such as *Bombusterrestris* have been employed to vector *Clonostachysrosea*for the management of grey mould (*Botrytis cinerea*) in strawberries and raspberries. Their relatively localized foraging behavior, ability to buzz-pollinate, and activity under low-light or cooler conditions make them highly suitable for controlled environments.

**Solitary bees** such as *Osmia* spp. (mason bees) and *Megachile* spp. (leafcutter bees) also show potential as entomovectors, especially in orchards and seed crops where they are already used for managed pollination. Their nesting habits and flower constancy allow for reliable inoculum transfer within a specific crop system.

Beyond bees, other insects including flies, beetles, and thrips have been explored as potential vectors, although their use remains limited compared to bees. Research suggests that syrphid flies and certain beetles may play supplementary roles in microbial delivery, particularly in ecosystems where bee populations are scarce or crop pollination depends on alternative flower visitors.

**Microbial and Biocontrol Agents**

The effectiveness of entomovectoring is strongly determined by the microbial or biocontrol agents being delivered to plants. These agents are typically antagonistic microorganisms that suppress plant pathogens, promote plant growth, or improve crop resilience against stress factors. The choice of an appropriate microbe depends on its ability to adhere to insect bodies, remain viable during transport, colonize floral tissues, and effectively compete with or inhibit plant pathogens.

**Fungal antagonists** are the most widely studied group in entomovectoring. Species such as *Clonostachysrosea* and *Trichoderma harzianum* have been frequently employed against *Botrytis cinerea*, the causal agent of grey mould in strawberries, grapes, and tomatoes. These fungi suppress pathogens through multiple mechanisms, including competition for nutrients and space, mycoparasitism, and production of antifungal metabolites. *Gliocladiumcatenulatum* has also been successfully vectored by bees to manage diseases in greenhouse crops.

**Bacterial agents** are increasingly gaining attention as promising candidates. Plant growth-promoting rhizobacteria (PGPR) such as *Bacillus subtilis* and *Pseudomonas fluorescens* can be vectored to flowers, where they inhibit pathogens and stimulate systemic resistance in plants. For example, *Bacillus* strains are being tested for their ability to suppress fire blight (*Erwiniaamylovora*) in apple and pear orchards through bee-mediated delivery.

**Yeasts** represent another important group, particularly due to their natural occurrence on floral surfaces and compatibility with insect vectors. Species like *Aureobasidium pullulans* and *Cryptococcus* spp. have shown potential in controlling postharvest fruit diseases. Yeasts are generally robust, tolerate desiccation, and can easily colonize floral tissues, making them attractive agents for entomovectoring systems.

Recent research has also highlighted novel microbial agents including endophytes, entomopathogenic fungi with non-lethal roles, and engineered microorganisms with enhanced antagonistic traits. Advances in biotechnology and formulation science are improving the stability, adherence, and delivery efficiency of these agents, thereby widening the scope of entomovectoring in sustainable agriculture.

**Mechanism of Entomovectoring:**

**Competition:**

Competition is one of the primary mechanisms by which microbial agents suppress plant pathogens in entomovectoring systems. Beneficial microbes delivered by insect vectors colonize floral tissues and infection courts, thereby occupying physical space and consuming available nutrients that would otherwise be exploited by pathogens. This ecological exclusion reduces the chances of pathogen establishment and growth. For example, *Clonostachysrosea* effectively colonizes strawberry flowers, limiting the access of *Botrytis cinerea* to infection sites.

**Antibiosis:**

Antibiosis refers to the ability of beneficial microbes to produce bioactive substances that directly inhibit the growth or activity of plant pathogens. These substances include antibiotics, cell wall–degrading enzymes such as chitinases and glucanases, and volatile organic compounds

(VOCs) with antifungal or antibacterial activity. For instance, *Trichoderma harzianum* secretes enzymes that degrade the hyphae of fungal pathogens, while *Bacillus subtilis* produces lipopeptides that suppress bacterial and fungal diseases. This direct antagonistic interaction plays a crucial role in preventing pathogen infection and spread.

**Induced Resistance:**

Some entomovectored microbial agents enhance plant defense by triggering physiological and molecular responses that strengthen resistance to pathogens. This phenomenon is referred to as induced resistance and can occur in two forms: Systemic Acquired Resistance (SAR), which is mediated by salicylic acid pathways and often linked to pathogen-associated molecular patterns, and Induced Systemic Resistance (ISR), typically associated with beneficial rhizobacteria and mediated by jasmonic acid and ethylene pathways. For example, *Pseudomonas fluorescens* and *Bacillus* spp. are known to elicit ISR, leading to enhanced plant immunity and reduced susceptibility to diseases.

**Mycoparasitism**

Mycoparasitism is a direct mechanism in which beneficial fungi parasitize pathogenic fungi, attacking and killing them. Entomovectored fungal biocontrol agents, such as *Trichoderma* spp., can coil around the hyphae of pathogens, penetrate their cell walls, and degrade them using lytic enzymes. This direct parasitic interaction effectively suppresses pathogen growth and spread. For example, *Trichoderma harzianum* parasitizes *Botrytis cinerea* on strawberry and tomato flowers, reducing disease incidence while also being safe for the plant. This mechanism complements competition, antibiosis, and induced resistance, enhancing the overall efficacy of entomovectoring.

**Applications in Crop Protection**

Entomovectoring has emerged as a sustainable and eco-friendly strategy for protecting crops from various diseases while simultaneously ensuring pollination. By using insects such as honey bees, bumblebees, and solitary bees as vectors, beneficial microbial agents can be delivered directly to flowers or plant surfaces, where they suppress pathogens and enhance plant health. This approach has been successfully applied in controlling grey mould (*Botrytis cinerea*) in strawberries, tomatoes, and cucumbers using fungi like *Trichoderma harzianum* and *Clonostachysrosea*. Bacterial agents such as *Bacillus subtilis* and *Pseudomonas fluorescens* have been used to induce systemic resistance and inhibit a range of fungal and bacterial pathogens in fruits, vegetables, and seed crops. Entomovectoring also complements integrated pest management (IPM) by reducing reliance on chemical pesticides, lowering environmental contamination, and maintaining beneficial insect populations. Beyond disease control, it contributes to crop yield improvement by enhancing pollination efficiency, making it a dual-benefit tool for sustainable and climate-smart agriculture. Recent studies have also explored large-scale adoption and commercialization, highlighting its potential for greenhouse crops, open-field horticulture, and seed production systems worldwide.

**Integration with IPM**

Entomovectoring fits seamlessly into the framework of Integrated Pest Management (IPM) by providing an environmentally friendly and targeted approach to disease control while simultaneously supporting pollination services. In conventional IPM, multiple strategies—cultural practices, biological control, mechanical methods, and judicious chemical use—are combined to manage pests and diseases sustainably. Entomovectoring complements these strategies by enabling beneficial microorganisms, such as *Clonostachysrosea* and *Trichoderma* species, to be delivered directly to plant surfaces via pollinators like honeybees and bumblebees. This targeted delivery reduces the need for broad-spectrum chemical fungicides, minimizing non-target effects on beneficial insects and soil microbiota. Additionally, entomovectoring can be integrated with cultural practices, such as optimized planting schedules and sanitation measures, to enhance disease suppression. Field trials have shown that entomovectoring can be combined with minimal chemical interventions without compromising efficacy, making it a practical component of IPM programs in crops such as strawberries, tomatoes, cucumbers, and apples. By synchronizing microbial delivery with the foraging activity of pollinators, entomovectoring not only manages plant pathogens effectively but also supports crop productivity and ecological balance, exemplifying a holistic, sustainable, and climate-smart approach to pest and disease management.

**Environmental and Human Health Benefits**

By lowering chemical pesticide use, entomovectoring minimizes drift, runoff, and soil contamination, protecting ecosystems and human health. Reduced residues lower risks for workers and consumers while conserving pollinators, predators, and soil microbes. This supports biodiversity, ecological balance, and plant resilience, aligning with sustainable and climate-smart agriculture.

**Challenges and Ecological Constraints**

Adoption is limited by pollinator behavior, weather, and compatibility between microbes and vectors. Microbial stability, field performance, and ecological risks such as non-target impacts also present challenges. Environmental factors like temperature, rainfall, and habitat fragmentation influence foraging and microbial survival. Managing these requires careful field research and adaptive strategies.

**Technical and Economic Issues**

Effective dispenser design, microbial formulation, and colony management demand expertise and cost. Ensuring uniform application in diverse crops and training farmers add complexity. Economic feasibility is critical, as costs of pollinator upkeep and microbial production may deter smallholders. Cost-benefit analyses and affordable formulations are needed to ensure adoption.

**Future Prospects and Conclusion:**

Advances in microbial formulations, encapsulation, and precision agriculture tools can enhance efficacy and reduce costs. Policy support, regulatory frameworks, and public-private partnerships will be essential for scaling. With ongoing innovation and integration into IPM, entomovectoring offers a climate-smart, eco-friendly approach that combines pollination with plant disease management, holding strong promise for sustainable agriculture.

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# PHYTOTOXICITY AND RESIDUAL TOXICITY OF HERBICIDES AND REMEDIAL MEASURES

**Nagesh Rathod*[1], Sajjan G[1], Aditya Kamalakar Kanade[2], Kumar D Lamani[1] and G Somanagouda[1]**

[1]University of Agricultural Sciences, Dharwad, Karnataka, India-580005

[2]Mahatma Phule Krish Vidyapith, Rahuri-413722, Maharashtra, India

*Corresponding author E-mail: nagesh551999@gmail.com

**Abstract:**

The increasing global population and the consequent demand for higher agricultural productivity have led to intensified herbicide use, especially in regions facing labour shortages, such as India. While herbicides are effective in managing weed infestations and improving crop yields, their indiscriminate and excessive use can result in phytotoxicity to non-target plant species and residual toxicity in soil ecosystems. Phytotoxicity manifests as growth inhibition, chlorosis, necrosis, and yield reduction, affecting both crops and native vegetation. Residual herbicide toxicity disrupts soil microbial dynamics, nutrient cycling, and can have long-term implications on soil health, plant growth, biodiversity, and food safety. Several factors influence herbicide toxicity, including herbicide type, dosage, environmental conditions, soil properties, and application timing. Effective management strategies such as integrated weed management (IWM), use of herbicide-tolerant crops, crop rotation, phytoremediation, and the application of farmyard manure, activated charcoal, and safeners help mitigate these adverse effects. Advanced approaches like bioaugmentation and biostimulation offer promising solutions for degrading persistent herbicide residues. A balanced approach, emphasizing responsible herbicide use, environmental conservation, and sustainable agricultural practices, is crucial to minimize the ecological and agronomic risks associated with herbicide phytotoxicity and residual toxicity.

**Keywords:** Factors, Herbicides, Management practices, Phytotoxicity, Residual Toxicity.

**Introduction:**

The global population goes on increased year after year it create pressure on agriculture due to food demand. Labour shortage is one of the major problems in world as well as India in agriculture field. In agriculture field crop yield losses due to weed is more up to 35 to 80 percentage some time due to improper weed management practices. Indian formers used large quantity of herbicides for weed control in agriculture field due to shortage of labour for hand weeding. By using large quantity of herbicides, it causes phytotoxicity on non-target plant and residual effect on soil microbial activity.

The global population is growing at a faster rate and it has reached to 7.8 billion in 2020. It is estimated to grow further up to 8.5 billion by 2030, 9.7 billion by 2050 and to 10.9 billion by the year 2100 with present trends of population growth rate. The food production in 2050 will need to increase by 50 percent as compared to 2012 to address the food grain demand. Achieving this projected demand and sustaining the production and productivity levels will be a major challenge in years to come. Adoption of high-yielding varieties, fertilizer application, irrigation and plant protection will remain the most likely options to achieve intensification in agriculture to combat these challenges. However, in recent years the global emphasis has shifted from improving potential yield levels to environmental concerns, soil health, reducing costs of production and reducing dependency on plant protection measures. Thus, sustainability of future agricultural systems, in the years to come will remain even greater challenge than the present scenario.

Management of weeds is considered to be an important factor for achieving higher productivity as weed problem is more severe during continuous rains in early stages of different crops growth which cannot be controlled by traditional and cultural practices alone due to too much wetness and labour scarcity. Weed infestation is one of the major constraints for low yield of different crops as weeds compete with crop plants for essential inputs. Weed depletes 30-40% of applied nutrients from the soil. The quantities of growth factors used by weeds are thus unavailable to the crop.

The sustainable agriculture involves optimizing agricultural resources and at the same time maintaining the quality of environment and sustaining natural resources. In achieving this optimization, the soil microbial community composition is of great importance, because they play a crucial role in carbon flow, nutrient cycling and litter decomposition, which in turn affect soil fertility and plant growth and hence occupy a unique position in biological cycles in terrestrial habitat. The soil microbial biomass is considered as active nutrient pool to plants and plays an important role in nutrient cycling and decomposition in ecosystem. A healthy population of soil microorganisms can stabilize the ecological system in soil (Baboo *et al.,* 2013) due to their ability to regenerate nutrients to support plant growth. Any change in their population and activity may affect nutrient cycling as well as availability of nutrients, which indirectly affect productivity and other soil functions.

Natural and anthropogenic factors may affect the soil enzyme activities directly or indirectly. Among anthropogenic factors, pesticides are of primary importance due to their continuous entry into the soil environment. Herbicides are one of the major groups of pesticides, which include substances or cultured biological organism used to kill or suppress the growth of unwanted plants and vegetation in order to minimize the cultivation cost as well as to sustain high yield. A number of herbicides have not only been introduced as pre- or post-emergence weed killer but also leave unwanted residues in soil, which are ecologically harmful. Preferred herbicides should not only have good efficacy, but also poses minimum adverse effects to crop, ecology and environment. Herbicides not only affect the target organisms, but also microbial communities in soil. These non-target effects may reduce the performance of important soil functions and poses a risk to the entire ecological system by (a) changing their biosynthetic mechanism, (b) affecting protein synthesis, (c) affecting cellular membrane, and (d) affecting plant growth regulators (Baboo *et al.,* 2013).

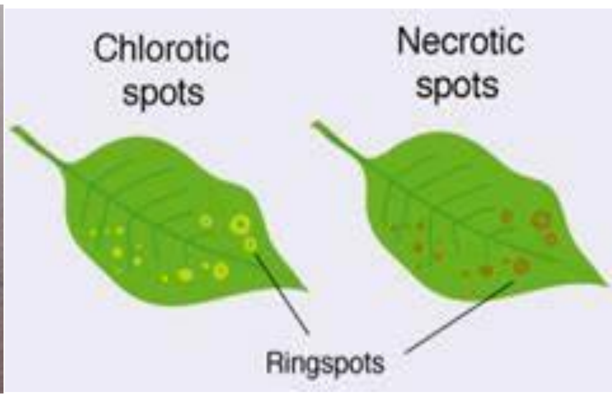
- Herbicides are chemical substances used to control unwanted plants or weeds, in agriculture and various land management practices.
- Phytotoxicity refers to the incidental harm caused to plants, including crops and native vegetation, by herbicide exposure.
- Phytotoxic effects can include stunted growth, leaf damage, yield reduction and even plant death.
- Residual toxicity involves the long-lasting presence of herbicides in the environment, potentially impacting non-target species and ecosystems.
- Herbicides can persist in the soil, water bodies and food chains, posing risks to the environment and in some cases, human health.
- Responsible herbicide use, proper application techniques and remedial measures are essential to mitigate adverse effects on plants and the environment.
- Understanding and addressing phytotoxicity and residual toxicity are crucial for sustainable agriculture and environmental conservation

**Phytotoxicity of Herbicides**

Phytotoxicity refers to the unexpected harmful effects of herbicides on plants, including both cultivated and non-target species.

**Varied Effects of Phytotoxicity of Herbicides**

- **Growth Inhibition:** Herbicides can slow down or inhibit the growth of plants, resulting in stunted development and reduced biomass.
- **Leaf Damage:** Phytotoxicity often manifests as damage to leaves, including browning, yellowing, wilting and necrosis (cell death).
- **Chlorosis:** One of the common effect is chlorosis, where leaves lose their green color due to a decrease in chlorophyll production, leading to reduced photosynthesis.
- **Leaf Deformation:** Some herbicides can cause leaves to become distorted, twisted, or misshapen.
- **Reduced Reproduction:** Phytotoxic herbicides may interfere with the reproductive structures of plants, leading to reduced flower production and seed set.
- **Root Damage:** Below-ground effects can include damage to roots, reducing a plant's ability to take up water and nutrients.
- **Yield Reduction:** In agricultural settings, phytotoxicity can significantly impact crop yields, leading to economic losses.
- **Delayed Maturity:** Herbicide exposure can delay the maturation of plants, affecting the timing of harvest in agriculture.
- **Loss of Competitive Advantage:** Weeds that are more tolerant of herbicides can thrive, leading to shifts in plant community dynamics.
- **Impact on Ecosystems:** Beyond crop plants, phytotoxicity can affect native vegetation, potentially disrupting ecosystems and habitats.




**Phytotoxicity of Herbicides**

**Herbicide type**

1. **Pre-Emergence Herbicides**

**Symptoms**

1. Reduce germination
2. Suppresses crop growth
3. Produces deformility in crop plants

**2. Post-Emergence Herbicides**

**Symptoms**

1. Leaf injury
2. Wilting
3. Vein clearing
4. Necrosis
5. Epinasty
6. Hyponasty
7. Yellowing or chlorosis
8. Sunting or scorching


**Plate 1: A sulfonylurea-sensitive corn hybrid with a crop response warning for the use of unsafened sulfonylurea herbicides following postemergence application with unsafened (left) and safened (right) sulfonylurea herbicide.**

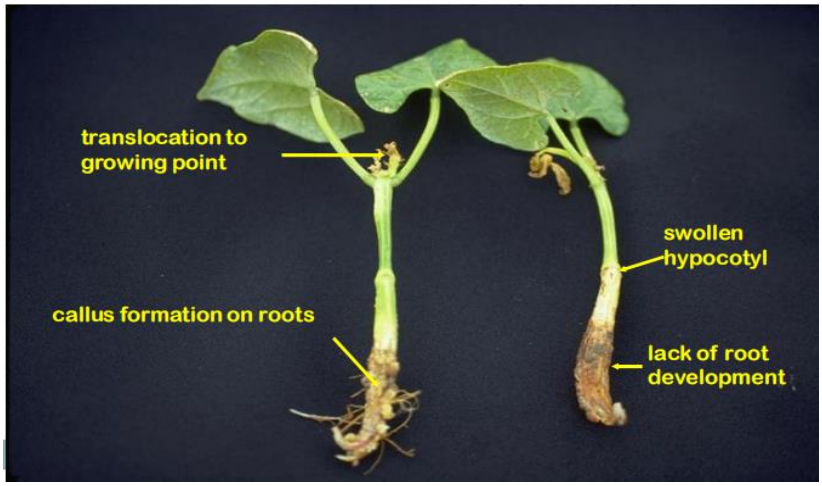



**Plate 2: Root absorption of plant growth regulator herbicides**

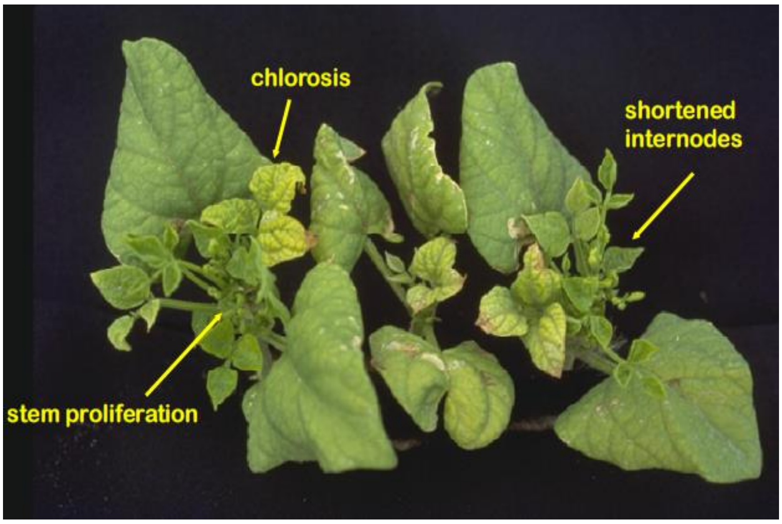



**Plate 3: Glyphosate drift**

**Selective vs. Non-Selective of Phytotoxicity of Herbicides**

- **Targeted Action:** Selective herbicides are designed to target specific types of plants, such as broadleaf weeds or grasses, while sparing others.
- **Crop Safety:** These herbicides are often used in agriculture alongside crops because they are formulated to harm weeds but not the cultivated plants.
- **Reduced Phytotoxicity:** Selective herbicides generally have reduced phytotoxicity on the crop species they are designed to protect.
- **Common in Lawn Care:** Selective herbicides are commonly used in lawn care to eliminate unwanted weeds without harming the grass.

  **Examples:** 2,4-D (a broadleaf weed killer), and clethodim (selective grass herbicide).

  **Non-Selective Herbicides:**

- **Broad-Spectrum Action:** Non-selective herbicides are designed to kill or damage most plant species they come into contact with.
- **Limited Crop Use:** They are not typically used in crop fields because they would harm both weeds and cultivated crops.
- **Comprehensive Phytotoxicity:** Non-selective herbicides have a higher potential for causing phytotoxicity to a wide range of plants.
- **Common Uses:** Non-selective herbicides are often used for total vegetation control in areas like driveways, sidewalks, and industrial sites.

  **Examples:** Glyphosate (widely used in products like Roundup), paraquat, and glufosinate.

**Factors Influencing Phytotoxicity of Herbicides**

- **Herbicide Type:** Different herbicides have varying modes of action and chemical properties, which affect their phytotoxicity. Some herbicides are inherently more toxic to plants than others.

- **Dosage and Concentration:** The amount of herbicide applied, measured as dosage or concentration, plays a significant role in determining the extent of phytotoxicity. Higher doses often lead to more severe damage.
- **Application Timing:** The stage of growth of the target and non-target plants when the herbicide is applied can impact phytotoxicity. Some plants are more sensitive at certain growth stages.
- **Environmental Conditions:** Weather and environmental factors, such as temperature, humidity, and sunlight, can influence how plants react to herbicides. For example, herbicides may be more effective and potentially more phytotoxic under specific conditions.
- **Plant Species Sensitivity:** Different plant species vary in their sensitivity to herbicides. Some plants are more tolerant and can withstand exposure, while others are highly susceptible.
- **Soil Factors:** Soil type, composition, and organic matter content can affect herbicide persistence in the soil, which, in turn, can impact phytotoxicity.
- **Herbicide Mode of Action:** The specific mechanism through which a herbicide works can determine which plant species it affects. Some herbicides target specific biochemical pathways, making them more selective.
- **Plant Health:** The overall health of the plants, including factors like nutrition, stress, and disease, can influence their vulnerability to herbicide phytotoxicity.
- **Mixtures and Tank Combinations:** The use of multiple herbicides or tank-mix combinations can interact in ways that affect phytotoxicity differently than when used individually.
- **Residue Accumulation:** Repeated herbicide applications can lead to residue buildup in the soil, increasing the risk of phytotoxicity to subsequent crops or plants.
- **Adjuvants and Formulations:** Adjuvants, added to herbicide formulations, can affect the herbicide's effectiveness and phytotoxicity. Formulation type, such as liquid or granular, can also influence how the herbicide interacts with plants.

**Crop Tolerance Against Phytotoxicity of Herbicides**

- **Crop Varieties:** Some crop varieties have developed natural or genetic tolerance to specific herbicides.
- **Tolerance Mechanisms:** Tolerance mechanisms can include enhanced detoxification, altered target sites, or metabolic pathways that allow the crop to withstand herbicide exposure.
- **Selective Herbicides:** Tolerant crop varieties are often used alongside selective herbicides that are specifically designed to harm weeds while sparing the crop.

- **Increased Yield and Weed Control:** Crop tolerance to certain herbicides can result in increased crop yield and improved weed control when combined with the right herbicide choice.
- **Herbicide Resistance:** In some cases, overreliance on herbicides can lead to the development of herbicide-resistant weeds that can overwhelm tolerant crop varieties.
- **Crop Rotation:** Crop rotation can be a strategy to minimize the development of herbicide-resistant weeds and maintain the effectiveness of tolerant crops.
- **Genetic Modification:** Some crops are genetically modified to express herbicide tolerance, making them more resistant to specific herbicides.
- **Sustainable Agriculture:** Tolerant crop varieties are an essential component of sustainable agriculture practices, enabling effective weed control while reducing the need for excessive herbicide use.
- **Economic Benefits:** Tolerant crops can lead to economic benefits for farmers by reducing the impact of weed competition on crop yields.
- **Herbicide Choice:** The choice of herbicide should align with the tolerance of the crop to avoid unintended phytotoxicity while targeting weeds effectively.

**Long-Term Effects of Phytotoxicity of Herbicides**

- **Soil Residue Accumulation:** Herbicides can persist in the soil for extended periods, leading to a buildup of residues that can affect future crops.
- **Residual Herbicide Activity:** Residual herbicide activity can continue to suppress weed growth long after the initial application, potentially impacting crop rotations.
- **Altered Soil Microbiota:** Herbicide residues may affect the composition and activity of soil microorganisms, disrupting soil health and nutrient cycling.
- **Herbicide Resistance:** Over time, repeated use of the same herbicide can lead to the development of herbicide-resistant weeds, making weed control more challenging.
- **Ecological Disruption:** Herbicide residues can disrupt local ecosystems by affecting non-target plant species, insects, and other wildlife.
- **Aquatic Ecosystem Impact:** Herbicides that leach into water bodies can have long-term effects on aquatic ecosystems, potentially leading to water quality issues and harm to aquatic organisms.
- **Shifts in Plant Communities:** Long-term exposure to herbicides can lead to shifts in plant community dynamics, favoring species that are more tolerant to the herbicide.
- **Pesticide Bioaccumulation:** Herbicides may accumulate in the food chain, impacting animals that consume plants treated with herbicides and potentially affecting higher trophic levels.

- **Soil Health Decline:** Herbicide residues can lead to soil degradation, including decreased organic matter and impaired soil structure.
- **Chronic Environmental Impact:** Long-term phytotoxicity can have chronic environmental effects, altering natural habitats and ecosystem stability.
- **Human Health Concerns:** If herbicide residues persist in food crops, they may pose long-term health concerns for consumers who ingest these residues.
- **Regulatory Implications:** Long-term effects may prompt regulatory changes to mitigate the environmental and health risks associated with herbicide use.

**How to Differentiate Phytotoxicity from Other Damages**

Symptoms of phytotoxicity can be confused with damages caused by plant pathogenic organisms or genetic disorders.

**Look for the following patterns to identify damage due to chemicals:**

- Leaf damage patterns show sharp edges with no discoloration gradient
- Plants very close to the sprayer show more damage than plants further away from the sprayer
- Symptoms show up fast in a wide area (1-7 days after application), and there is no further spread after the initial show-up.
- New growth will appear healthy.
- If there is a doubt upload images of the affected plant to the Agrio. app, and our artificial intelligence will help you with the identification

**Remedial Measures of Phytotoxicity of Herbicides**

- **Soil Testing:** Regular soil testing can identify the presence of herbicide residues and guide decision-making for planting suitable crops.
- **Crop Selection:** Choose crop varieties that are less sensitive to the specific herbicides used, reducing the risk of phytotoxicity.
- **Crop Rotation:** Implement crop rotation to break the cycle of herbicide persistence and avoid planting susceptible crops in contaminated areas.
- **Alternative Herbicides:** Consider using herbicides with shorter half-lives in the environment and lower phytotoxicity to reduce long-term effects.
- **Buffer Zones:** Establish buffer zones between treated areas and sensitive habitats to reduce herbicide drift and runoff.
- **Herbicide Application Timing:** Apply herbicides at the appropriate growth stage of target weeds to maximize efficacy and minimize phytotoxicity to crops.
- **Follow Label Instructions:** Always adhere to herbicide label instructions regarding application rates, timing, and safety precautions.

- **Precision Application:** Use precision application technologies to target herbicides only where needed, minimizing non-target exposure.
- **Crop Covers:** Utilize crop covers or mulches to protect crops from herbicide drift and contact.
- **Residue Management:** Manage herbicide residues by incorporating organic matter into the soil and promoting microbial degradation.
- **Phytoremediation:** Consider phytoremediation techniques, which involve planting specific crops to absorb and detoxify herbicides from the soil.
- **Monitoring and Research:** Continually monitor fields for signs of phytotoxicity and conduct research to better understand herbicide interactions with plants and ecosystems.
- **Regulatory Compliance:** Ensure compliance with local regulations and restrictions on herbicide use to protect the environment and human health.
- **Education and Training:** Educate farmers, applicators, and land managers about best practices and the risks associated with herbicide use.

**Table 1: Relative Persistence of Some Herbicides in soil.**

| < 1 months | 1-3 months | 3-6 months | >6 months |
|---|---|---|---|
| 2,4-D | Alachlor, Acetochlor, | Clomazone, | Atrazine, Bromacil, |
| Glyphosate | Ametryn, Anilofos, | Chlorimuronethyl, | Chlorsulfuron, |
| MCPA | Bispyribac-sodium, | Diallate, Dithiopyr, | Diuron, Diquat, |
| | Butachlor, Dalapon, | Ethofumesate, | Imazapyr, Picloram |
| | Carfentrazone-ethyl, | Fluchloralin, | Sulfentrazone, |
| | Fluazifop-butyl, Halosulfuron | Imazethapyr, | Sulfometuron, |
| | Metribuzin, Metamifop, | Isoproturon, | Simazine, Paraquat, |
| | Metsulfuron-methyl, | Metamitron | Trifluralin |
| | Metolachlor, Oxyfluorfen, | Oxadiazon, | |
| | Propachlor, | Linuron, Pyrazon | |
| | Pyrazosulfuron-ethyl | Pendimethalin | |

**Residual Toxicity of Herbicides**

**Herbicide Residue**

- ❖ "Herbicide residue" means any specified substances in food, agricultural commodities, or animal feed resulting from the use of a herbicide. The term includes any derivatives of a herbicide, such as conversion products, metabolites, reaction products and impurities considered to be of toxicological significance.
- ❖ Herbicides when applied to soil to control weeds should not remain in soil for long period. The length of time a herbicide remains active in soil is called "soil persistence," or "soil residual life".

- ❖ Herbicides that are persistent include triazines, uracils, sulfonylureas, dinitroanilines, imidazolinones and certain plant growth regulators belonging to the pyridine family.

**Half-life of Herbicide**

- The gauge by which we can predict herbicide persistence is half life of Herbicide.
- Herbicide half-life is a measure of how long it takes for 50% of a chemical to degrade.


**Figure 1: Herbicide half life**

**Factors Affecting Herbicide Carryover**

1. **Herbicide characteristics**
   - ➢ Adsorption
   - ➢ Water solubility
   - ➢ Volatility
2. **Herbicide degradation**
   - ➢ Microbial decomposition
   - ➢ Chemical degradation
   - ➢ Photodecomposition
3. **Soli factors**
   - ➢ Soil pH
   - ➢ Organic matter
   - ➢ Soli texture
   - ➢ Soil moisture
   - ➢ Soil temperature
4. **Plant uptake-** once plant absorb the herbicide, it is metabolized. This effectively removes residues from the soil. When plant stand densities are low, removal of herbicide residues is also low.

**Management Factors**

a) **Application Rate:** The higher the initial application rate, the longer it will take for the herbicide residue to dissipate.

b) **Time of Application:** The greater the amount of time between the application and the seeding of a sensitive crop, the less likely injury will occur.

c) **Use Patterns:** Consecutive application of the same or related herbicides can increase the risk to rotational crops. The use of residual herbicides from the same Herbicide Group can result in an additive or cumulative effect, potentially limiting crop choices the following year. Keeping good field records and avoid back-to-back use, this management strategy will assist in minimizing re-crop concerns.

d) **Uniformity of application/incorporation:** Residual herbicides that have been applied and incorporated at recommended rates should not be a problem the following season. Non-uniform application or incorporation can cause hot spots where higher than recommended concentrations of herbicide occur in patches.

e) **Tillage System:** In direct-seeded fields where minimal disturbance is done, the herbicide residues remain in a concentrated band on the soil surface. In a conventional tillage system, tillage mixes the herbicide residues throughout the soil profile, accelerating rates of microbial degradation and diluting the herbicide residues.

f) **Fertility and Plant Growth:** If the soil is low in fertility, the growth of microorganisms and the degradation of herbicides is slower

**1. Cultural and Mechanical Management Practices**

**a) Through integrated weed management**

- ❖ IWM involves the application of a variety of management practices to control weeds.
- ❖ Herbicides are used only when weed populations exceed an economic threshold level.
- ❖ Non chemical weed control methods are emphasized.

**b) Growing herbicide tolerant crops**

- ❖ Certain herbicide tolerant crops reduce herbicide residues in a soil by absorbing and deactivating these in their tissues.
- ❖ Maize and millets - triazine herbicide.
- ❖ Methi, turnip, berseem and gobhi-sarson - sulfosulfuron.

**c) Light irrigation after application**

- ❖ Continuous moist soils often result in a more rapid breakdown of herbicides
- ❖ Creates favorable conditions for microbial activity.

**d) Ploughing or cultivating the land**

- ❖ Operations bring deep present herbicide residues to soil surface which aids in decontamination by degradation.
- ❖ The applied herbicide is mixed to a large volume of soil and gets diluted.
- ❖ Minimum or no-tillage generally have higher herbicide concentration near surface and can have carry over effect on succeeding crop.

2. **Deactivation of herbicides**

**a) Application of FYM**

- Adsorbs the herbicide molecules thus, making them unavailable for crops and weeds.
- The microbial population residing in the organic matter start decomposing the herbicide residues at a faster rate due to high WHC capacity of organic matter of soils.

**b) Use of adsorbents, protectants and antidotes**

- Applied to the soil, crop seed or transplanted plant to protect the crop from herbicide injury

**Mode of action**

- Either deactivation or adsorption of the herbicide
- Preventing its absorption and translocation by the crop.

**Activated charcoal**

- ❖ High adsorptive capacity
- ❖ Large surface area.
- ❖ Broadcasted or applied as narrow band over the seed at the time of planting.

**c) Use of Safeners**:

- ❖ A group of structurally diverse synthetic chemicals that protect crop plants from injury by certain herbicides.
- ❖ Improves herbicide selectivity between crops and weed species.

**3. Reducing the availability herbicide in the soil**

a) Use of optimum and reduced doses of herbicide

- More the quantity of herbicides application, more will be the residues releasing in to the soil. Hence, more will be the persistence.
- So herbicides should be applied at the least possible dose.

b) Use of herbicide in combination and sequential application

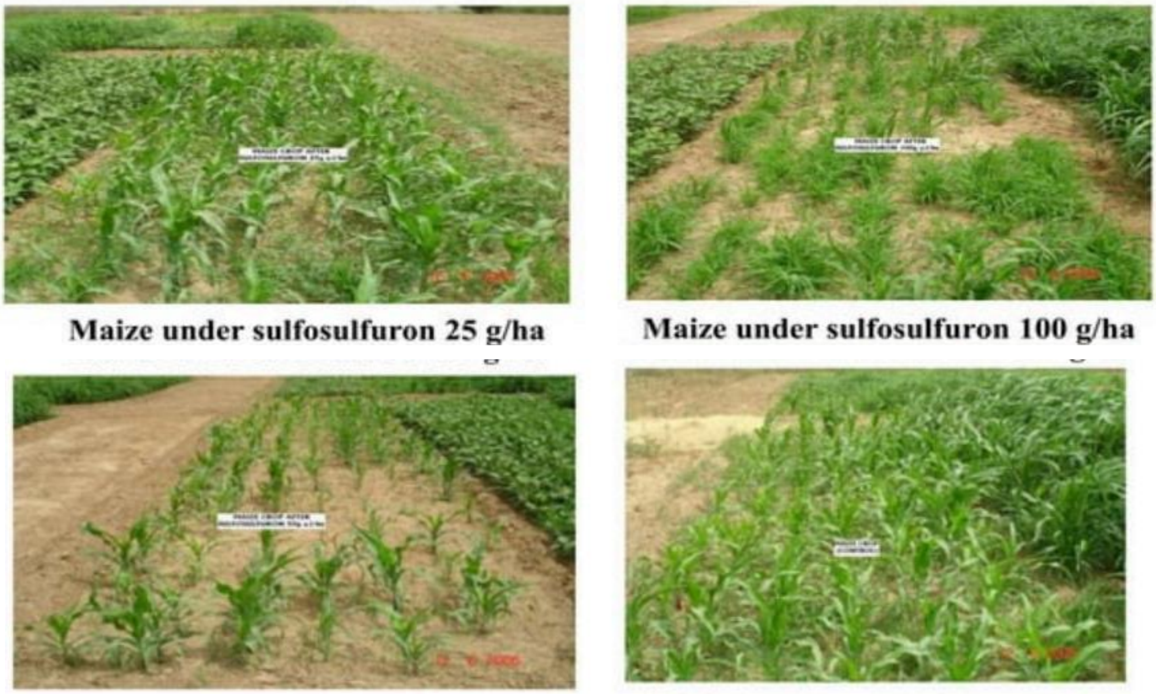
- The rate of application can be decreased by using herbicides in combination.
- Split application of herbicides will reduce the amount of herbicide available to runoff at any one given time

c) Use of alternatives to herbicides

- Plants excrete certain chemicals which inhibit the growth and germination of other plants growing in vicinity called Allelochemicals.
- Use of bioherbicides like Collego, DeVine etc.

d) Selection of herbicides with minimum carry-over potential

- Choose an herbicide with little or no carry-over given your local soil and weather conditions will future crop injury problems.



Maize under sulfosulfuron 25 g/ha    Maize under sulfosulfuron 100 g/ha

Maize under sulfosulfuron 50 g/ha    Maize under control

**Plate 4. Effect of different doses of herbicide on crop**

Application of sulfosufuron at the rate of 25 g/ha shows there is no phytotoxicity on maize crop and effectively control by weeds. Application of sulfosufuron at higher dosage causes phytotoxicity on maize plant as compared to 25 g/ha sulfosufuron application.

**4. Enhancing herbicide degradation**

**a) Biostimulation:**

- The addition of electron acceptors, electron donors, or nutrients to stimulate naturally occurring microbial populations is termed as Biostimulation.
- Introduction: of adequate amounts of water, nutrients, and oxygen into the soil to enhance the activity of indigenous microbial degraders.

**b) Bioaugmentation:**

- The Introduction: of specific microorganisms (indigenous or non-indigenous) aiming to enhance the biodegradation of target compound can be termed as Bioaugmentation.
- Microorganisms are capable of degrading the herbicide compounds in the soil by utilizing them as a supply of nutrients and energy.

**Conclusion:**

- Phytotoxicity and residual toxicity of herbicides pose challenges for agriculture and the environment.
- Remedial measures, including responsible herbicide use, education, and regulatory compliance, are crucial to minimize these impacts.

- Striking a balance between weed control and environmental protection is essential for sustainable agriculture and land management.
- Further, the combination of technologies like bioaugmentation, biostimulation, phytoremediation along with organic matter addition and crop rotation might be a promising technology for minimizing the herbicide residues and persistence in soil.

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# SOILLESS AGRICULTURE

**Sajjan. G*[1], Raju Chavan[2], D. Hemanth[3] and Rasheed. R. J[1]**

[1]College of Agriculture, Dharwad

[2]Department of Environmental Sciences, UAS, Dharwad

[3]Department of Agronomy, S. V. Agricultural College, Tirupati

*Corresponding author E-mail: sajjanguru123@gmail.com

**Introduction:**

Today, the world is facing many threats arising from human-induced changes in nature's systems. Global warming, which is probably the most widely known of these changes, causes the sea level to rise as a result of ice melting at the poles and a subsequent increase in the volume of sea water. There is widespread debate on exactly how far the sea level will rise in the near future, but it is clear that there are some places in the world where the sea level has already risen and affected people's lifestyles. Further, a warming planet will most probably have more frequent flash floods, intensive tropical storms, and rainfall. Along with these threats, the main challenge for present day farmers is "to feed the growingpopulation" in spite of the following facts:

- Increasing population growth and decreasing per capita land availability.
- Drought condition and unpredictability of climate and weather patterns.
- Soil degradation and improper use of manure, fertilizer and herbicides.
- Diminishing water availability for irrigation.

**Food Grains Availability in India Production:**

Over the last 20 years, total food grain production in India increased from 198 million tonnes to 269 million tonnes. Wheat and rice are the staple foods of Indians and are a major portion of food grain production, constituting around 75 percent of the total food grain production and thus serving as a major source of income and employment to millions of people. The state of Uttar Pradesh leads in the production of wheat, cereals and food grains, closely followed by Punjab and Madhya Pradesh. West Bengal is the 'rice bowl' of India, followed by Uttar Pradesh, Punjab and Bihar.

**Net Availability:**

Since 1996, the per capita net availability of food grains has increased from 475 to 484 g/capita/day in 2018, while per capita availability of pulses has increased from 33 to 55 g/capita/day. Although there has been a huge increase in production of rice, wheat and other cereals, their per capita net availability has not increased at the same level, due to population growth, food wastage and losses and exports.

**Production Trends:**

Between 1996-99 and 2015-18, the annual growth rate for food grains was 1.6 percent. Production growth for other major crops is: 2.4 percent for pulses, 1.8 percent for wheat, 1.6 percent for other cereals, 1.4 percent for rice, and 0.9 percent for bajra. Maize had the highest growth, at 5.9 percent. Conversely, other crops had declines in annual growth rates such as: jowar (-2.26 percent), small millets (-1.71 percent) and ragi (-1.21 percent).

The world's population is projected to reach 8.5 billion by 2030 and close to 10 billion by 2050. This will lead to a significant increase in demand for food and fibre as projections show that overall food production would have to be raised by some 70 percent towards 2050 while production in the developing countries would need to be almost do

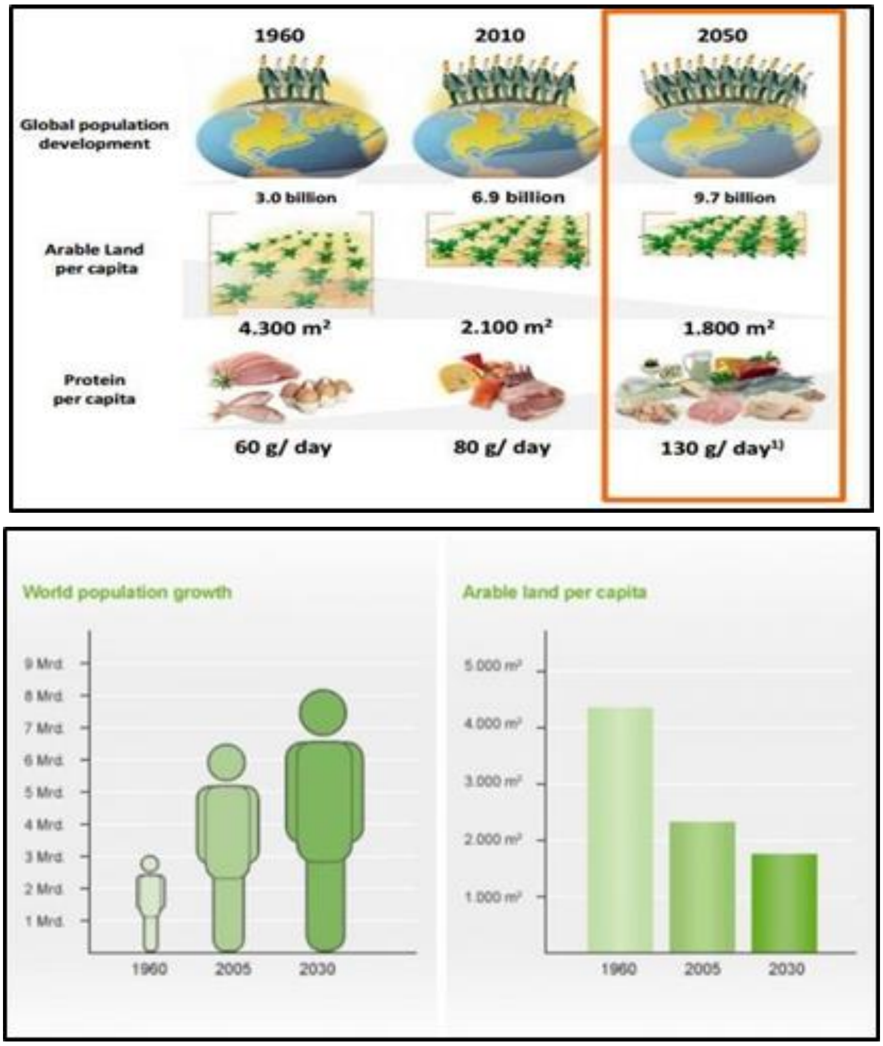



**Figure 1: Population growth and per capita land availability**

**Land Related Constraints**

- Decline in soil organic carbon
- Increase in soil salinity
- Increased incidence of soil borne diseases

**Water Related Constraints**

**Table 1: Per capita water availability in India**

| Year | Population (Millions) | Per capita water availability ($m^3 yr^{-1}$) |
|---|---|---|
| 1951 | 361 | 5177 |
| 1955 | 395 | 4732 |
| 1991 | 846 | 2209 |
| 2001 | 1027 | 1820 |
| 2025 | 1394 | 1341 |
| 2050 | 1640 | 1140 |

Similarly, present global water demand is projected to increase by 55% with increased stiff competition among various sectors. So major challenge would be to produce more with less water in a sustainable manner taking into account impacts of climate change and variability.

**Social Constraints**

- Increasing urban population
- Conversion of agricultural land
- Changes in employment share
- Increased labour cost

**Need for a Solution…!!!**

Since both land and water resources are finite resources, increased agricultural production to meet the requirement of the increasing population will have to come from the same limited net sown area by increasing productivity with an optimal use of available water and land resources. As water stress spreads around the globe, finding ways of getting more crop per drop to meet our food needs is among million hectares at present. Indians are demanding high quality, pesticide free, fresh produce. Money not the criterion. Growing demand for high quality, microbe free, medicinal and aromatic plants. People are aware of dangers of pesticides, global warming and its ill effects. Media plays an important role. Consistency, quality and yields possible only by modern techniques of cultivation. There is a need for technology in agriculture that can contribute towards water saving and have a positive impact on food production, security and availability.

**Soilless Farming**

Soilless cultivation generally refers to any method of growing plants without soil as a rooting medium. In detail, soilless farming is an artificial means of providing plants with support and a reservoir for nutrients and water. The simplest and oldest method for soilless farming is a vessel of water in which inorganic chemicals are dissolved to supply all of the nutrients that plants require. Often called solution culture or water culture, the method was originally termed as hydroponics (*i.e.*, "water working") by W. F. Gericke inthe 1930's.

**History of Soilless Farming**

Soilless farming technology was developed by German botanists Julius von Sachs and Wilhelm Knopp during the period 1859 to 1875. In India, it was started in the year 1946 byan English scientist WJ Shal to Douglas. He set up a laboratory in the Kalimpong area ofWest Bengal and wrote a book on hydroponics called Hydroponics - The Bengal System.

**Advantages and Limitations of Soilless Farming**

It is a feasible option for efficient use of land and water resource. In urban and peri-urban areas where arable land is polluted, its importance increases. According to the Food and Agriculture Organization (FAO), under soilless systems, vegetable production increases about 20–25% than conventional systems. But due to higher input cost, it is limited only to high value crops. It also required utmost care with regard to plant health, environment control and irrigation management.

**Benefits of Soilless Farming**

- ✓ Avoid soil borne pathogens and diseases
- ✓ Avoid of soil disinfection and treatment
- ✓ Cultivation of good quality green vegetables
- ✓ Precise nutrient application in inert media
- ✓ Higher yield and better quality of produce
- ✓ Land saving (50%) and water saving (90%)

**Limitations of Soilless Farming**

- ✓ Lack of skilled labours
- ✓ High initial investment
- ✓ Lack of awareness among the farmers and government subsidies
- ✓ Precise monitoring

**Classification of Soilless Farming**

It is classified into three types such as hydroponics, aeroponics and aquaponics, based on the type of substrates and containers, the nutrient system for the plant and drainage. In hydroponics, plants are grown in liquid medium contained in a pipe or container, which has two types of circulating and non-circulating systems. In case of circulating, the nutrient solution moves around the root zone of the plant and is collected, replenished and reused as per the requirement, which are mainly of Deep flow technique (DFT) and Nutrient Flow Technique (NFT) types whereas non-circulating system is a system in which the nutrient solution is not circulated but is used only once. These are mainly of three types such as capillary action, root deeping and floating technique. In Aeroponics, the nutrient solution is sprayed every 2-3 minutes for a few seconds by hanging the roots of the plant in the air suspended in the holes of the styrofoam panels and also properly watered and aerated as needed.It is found suitable for growing leafy vegetables such as spinach, lettuce, etc. inside protected structures. In this, double crops can be grown by efficient technology. However, Aquaponics is a type of aquaculture, in which fish and other aquatic animals and plants are easily grown using hydroponics method. In this system, fish faeces replenish the organic manure of the plants and the plants purify water for fish.

1. **Hydroponics**

"Hydroponics" refers to a soil-less growing system at either a commercial or residential level. These systems help plants grow by providing water and nutrients through a non-soil growing medium. Typical growing media include: vermiculite, perlite, coconut coir, rockwool/ stonewool, clay pellets, sand/gravel/sawdust and peat moss etc. Hydroponics removes the barriers between the plant and its nutrients. This provides the roots with direct access to water, oxygen, and nutrients that it needs to grow and survive. Because there's no soil, there is also no need for harmful pesticides or chemicals. There's also a lower risk of plant disease or exposure to external elements. Hydroponics is a soil-less culture technique in which plant can grow in a mineral nutrient solution.

**There are 2 systems in hydroponics, they are Passive and Active systems.**

- **Passive system**s rely on a wick or the anchor of the growing media.
- **Active systems** means that nutrient solutions will be moved, usually by a pump.

**Passive Systems:**

**1.1 Wicking systems**

The wick system is the most basic type of hydroponic process, also called "the training wheels of the hydroponic world." This kind of growth has actually been used for thousands of years, even before the term "hydroponic" was considered. In a wick system, the nutrients and water are transported to the plants' roots using a wick, like a rope or a piece of felt. The plants are suspended in some sort of growing medium, like coconut coir or perlite. Below the growing tank is a reservoir of water and nutrient solution. One end of the wick is in the solution and the other end of the wick is in the growing media. This allows the wick to transport the water and nutrients at the same rate that the plants' roots require the nutrients. Whenever the roots are ready to absorb, they'll take in the nutrients from the wick. Wick systems are "passive hydroponics" because they don't require air or water pumps. This makesthem low-cost and easy to maintain, especially for beginner growers.

**Pros:**

- The wick system is great for smaller plants

- Once implemented, it's an easy and hands-off growing process
- It's a good option for beginners or children gardeners
- Wick is one of the lowest cost systems to implement

**Cons:**

- Wicking is not effective for larger plants or extensive gardens
- Failure to set up properly or maintain the integrity of the wick can kill the plants

**Active Systems:**

**1.2 Deep Water Culture (DWC)**

The deep-water culture (DWC) is the easiest system to maintain for most growers. A DWC consists of a reservoir filled with water and nutrient solution. The plants are suspended over the reservoir using a net pot and growing media. The roots themselves are submerged in the reservoir, so they have a constant supply of water and nutrients. Plant roots need oxygenor they can "drown." Thus, you need to use an air pump with air stone to pump bubbles in the reservoir to continuously oxygenate the water and deliver necessary oxygen to the roots.

**Pros:**

- DWC is inexpensive and low-cost to maintain
- Upkeep is low and only requires a reservoir, suspension system, and basic air pumps
- It's a recirculating process, which means less waste and greater cost savings

**Cons:**

- DWC doesn't usually work for larger plants or those with a longer growing period
- If not properly managed, plant roots can suffocate in solution

**1.3 Nutrient Film Technique (NFT)**

The nutrient film technique (NFT) supplies the plans' roots with a thin film ofnutrients. The water and nutrient solution is held in a large reservoir, which has an air pump and air stone to stay oxygenated (like a DWC system). However, unlike the submerged roots of a DWC, NFT-system plants are grown in a nearby channel (in net pots). A water pump, set on a timer, pushes water through the channel. This delivers a thin film of nutrients and water to the plants, where the roots are not completely submerged. At the end of the channel, the solution drops back into the main reservoir to be reused in the system.

**Pros:**

- NFT is a low-waste recirculating system
- The film ensures you don't suffocate your roots
- There is minimal to no growing media needed

**Cons:**

- A malfunction in the pumps can ruin the crop

- Roots can overgrow and intertwine along the channel

### 1.4 Ebb and Flow

An ebb and flow system, also called “flood and drain,” floods your plants with nutrients on a cycle. This is a less common practice because it’s not as flexible to your plants’ needs. Some growers like this system, though, because it doesn’t continuously expose the plant roots to the nutrient solution. You fill a tray with a growing medium to house the plants. A timed pump will “flood” the tray with nutrient solution on a cyclic schedule. The cycle of flooding depends on the type of plants, water testing, the air temperature, the growth cycle, and more. After flooding the tray, gravity drains the solution back into the reservoir to be reused. An air pump should oxygenate the water in the reservoir as it waits for the next flood cycle. This system can work well if you have strong monitoring processes to understand your plants’ growth intake of nutrients.

**Pros:**

- An ebb and flow system doesn’t expose your plants to constant water. This can helpimprove growth and yield if appropriately cycled
- Ebb and flow are recirculating systems that are an efficient use of water and energy

**Cons:**

- If not balanced or timed properly, the system may over-saturate your plants or drythem out
- Ebb and flow require consistent monitoring, especially of environmental factors likewater pH

### 1.5 Drip Systems

Drip systems are usually found in commercial settings as opposed to residential because they’re better implemented on a large scale. These are similar to NFT systems, where the plants are held in a separate channel. The plants are suspended in net pots over a thin layer of water and nutrient solution. A pump continuously moves the water throughout the channel to improve oxygenation and nutrient uptake. Leftover solution flows back into the reservoir to be reused.

**Pros:**

- Drip systems offer greater control over the schedule of feeding
- For commercial spaces, these can be inexpensive and highly effective

**Cons:**

- These systems require a lot of moving parts, which could be overkill for homegardens
- You have to be highly aware of monitoring pH and nutrient levels

**Growth factors required by hydroponic plants:**

**Water:**

Plants require water for growth, and it has to be in sufficient quantities and of acceptable quality. It has a high mineral content, often accumulated while percolating through deposits of limestone and chalk, and is made up mostly of calcium and magnesium carbonates. This water typically has pH levels of eight or more. Municipal water is too alkaline for optimal hydroponic production, and always has a pH of about eight to prevent corrosion in plumbing. Proper drainage and aeration around underground roots are essential for root. In hydroponic systems, plants grow with their roots hanging in the nutrient solution, and dissolved oxygen (DO) levels in the solution should be high enough to promote root growth, and be carefully controlled.

**Air:**

Plants require $CO_2$ for photosynthesis, but it should be remembered that they also require oxygen ($O_2$) for respiration 24 hours a day. On sunny days, plants produce more O than is needed for respiration, but at night or in the dark underground root zones of terrestrial plants, only respiration occurs.

**Light:**

It is not only the amount of solar energy reaching the plants that is important, but day length, shading and the quality of light (consisting of a combination of ultraviolet, all the colours in the visible colour spectrum, and infrared (heat)).

Day length manipulation is often used to stimulate out-of- season flowering in plants such as chrysanthemums. There is also scientific evidence that ultraviolet light reduces stem lengths to make plants more compact (for example, potted poinsettias).

The blue portion of the light spectrum can be used for enhanced vegetative growth and to prevent flowering, or premature bolting in crops such as lettuce. Metal Halide Provides more blue/green spectrum for vegetative growth.

The red portion of the light spectrum can be used to increase stem length, stimulate flowering and fruit set, and is employed in growing roses. High Pressure Sodium provides more of the red/orange spectrum, great for flowering and fruiting.

Infrared (IR) radiation can be used to heat greenhouses and plants, but it can also scorch plants and may require shading to reduce radiation, or IR-controlled plastic covers to reduce solar radiation under warm conditions. Lightening determines what you can grow. Some plants such as vegetable require direct sunlight. Plants such as violets need indirect sunlight.

**Climate:**

Temperature and humidity are the most important climatic conditions that can influence plant growth. Frost can easily kill plants at sub-zero temperatures, or scorch them at high temperatures. However, pollination, fruit set and seed formation, germination and plant growth, among others, are all influenced by temperatures below or above the optimum range, long before frost damage or scorching occurs. Humidity plays a major role in transpiration and irrigation, but high humidity could cause fungal and other diseases.

**Nutrients:**

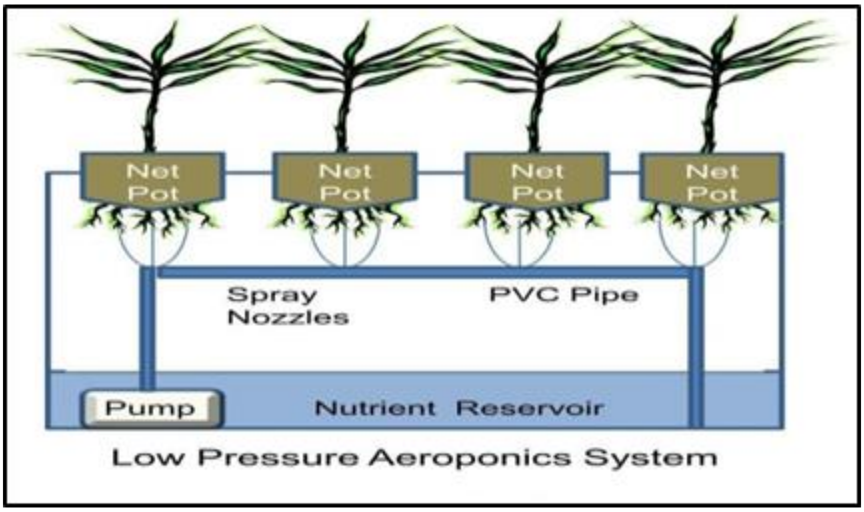
Plants require a total of 16 chemical elements to grow –some in relatively large quantities, and others, known as micro-nutrients, in minute amounts. These nutrients are also important to prevent slow or abnormal growth. Four of the six macro elements, carbon (C), hydrogen ($H_2$) and $O_2$, are readily available in nature in the form of water ($H_2O$) and air (consisting of $H_2$, $O_2$, $CO_2$ and nitrogen [$N_2$]). Fertilisers supply additional $N_2$, phosphorus and potassium in varying concentrations of up to 99%. The concentrations of chemicals used, acidity levels (pH) and DO levels of nutrient solutions are as important as their chemical contents.

2. **Aeroponics**

Aeroponics is a method of growing plants without soil where roots are suspended in the air and irrigated with a nutrient-dense mist.

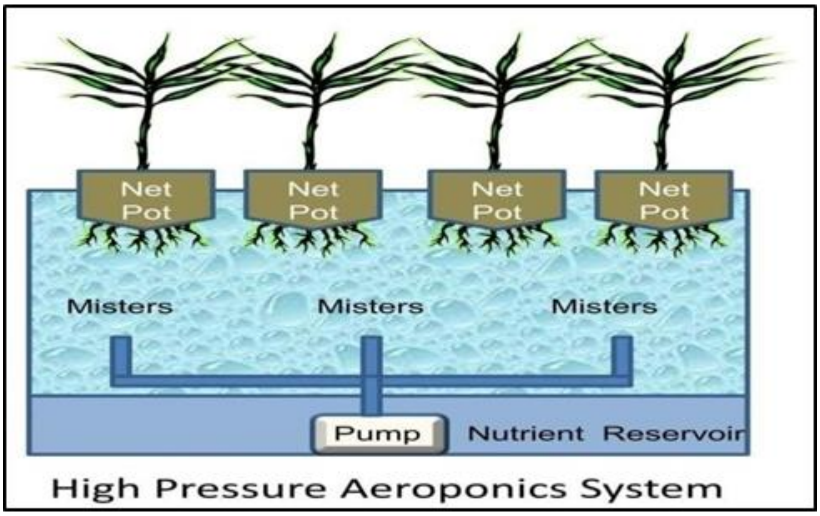
**Low-pressure units**

In most low-pressure aeroponic gardens, the plant roots are suspended above a reservoir of nutrient solution or inside a channel connected to a reservoir. A low-pressure pump delivers nutrient solution via jets or by ultrasonic transducers, which then drips or drains back into the reservoir. As plants grow to maturity in these units they tend to suffer from dry sections of the root systems, which prevent adequate nutrient uptake. These units, because of cost, lack features to purify the nutrient solution, and adequately remove incontinuities, debris, and unwanted pathogens. Such units are usually suitable for bench top growing and demonstrating the principles of aeroponics.



**High-pressure devices**

High-pressure aeroponic techniques, where the mist is generated by high-pressure pump(s), are typically used in the cultivation of high value crops and plant specimens that can offset the high setup costs associated with this method of horticulture. High-pressure aeroponics systems include technologies for air and water purification, nutrient sterilization, low-mass polymers and pressurized nutrient delivery systems.




**Commercial Systems**

Commercial aeroponic systems comprise high-pressure device hardware and biological systems. The biological systems matrix includes enhancements for extended plant life and crop maturation. Biological subsystems and hardware components include effluent controls systems, disease prevention, pathogen resistance features, precision timing and nutrient solution pressurization, heating and cooling sensors, thermal control of solutions, efficient photon-flux light arrays, spectrum filtration spanning, fail-safe sensors and protection, reduced maintenance & labour-saving features, and ergonomics and long-term reliability features. Commercial aeroponic systems, like the high-pressure devices, are used for the cultivation of high value crops where multiple crop rotations are achieved on an ongoing commercial basis.

1. **Aquaponics**

Aquaponics is the farming of fish and plants in a single recirculating system. The waste from the fish becomes the nutrients for the plants, and the plants in turn remove these nutrients from the water, purifying it for the fish.

**Biological Components of Aquaponics**

- Fish
- Plant
- Bacteria

**Functioning of Aquaponics**

The most important biological process in aquaponics is the nitrification process, which is an essential component of the overall nitrogen cycle seen in nature. Fish release ammonia in their waste. Bacteria in the water convert ammonia to nitrites, and then nitrites to nitrates. Plants need nitrates to grow, so they filter them out of the water clean water is pumped back into fish pond.

**Types of Aquaponics System**

1. **Raft or Deep-water culture system**

In a raft system (also known as float, deep channel and deep flow). The plants are grown on Styrofoam boards (rafts) that float on top of water. Water flows continuously from the fish tank, through filtration components, through the raft tank . where the plants aregrown and then water goes back to the fish tank.

2. **Media-filled bed**

A tank or container is filled with gravel, perlite or other media for the plant bed. This bed is periodically flooded with water from the fish tank. The water used by the plants. Then the water drains back to the fish tank. This method uses the fewest components and no additional filtration, making it simple to operate.

3. **Nutrient Film Technique**

Nutrient Film Technique is a method in which the plants are grown in long narrow channels. A thin film of water continuously flows down each channel, providing the plant roots with water, nutrients and oxygen.

**Conclusion:**

- Soilless agriculture, an innovative farming method, has emerged as a sustainable alternative to traditional soil-based cultivation.
- This approach minimizes the need for arable land, reduces water usage significantly compared to conventional farming and mitigates soil degradation and pest infestations.
- Furthermore, it allows year-round cultivation, offering higher yields, consistent quality and supports farming in urban and arid areas.
- Despite, challenges like high initial costs, technical expertise requirements and dependency on advanced infrastructure must be addressed to make it more accessible and widely adopted.
- Soilless agriculture enhances resource use efficiency, reduces pesticide use and thus reduces environmental impacts.
- The methods like hydroponics, aeroponics and aquaponics are promising technologies to promote sustainable food production for increasing population.

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# LEVERAGING ARTIFICIAL INTELLIGENCE TO MITIGATE CROP FAILURE

**Priyanka Chand*[1] and D. V. Singh[2]**

[1]Shri Vaishnav Vidyapeeth Vishwavidyalaya, Indore

[2]ICAR-ATARI, Patna

*Corresponding author E-mail: priyankachand.pc28@gmail.com

**Abstract:**

Crop failure remains one of the most serious challenges in agriculture, often triggered by unpredictable weather, soil degradation, pest outbreaks, and poor management practices. These failures threaten farmer livelihoods, disrupt markets, and endanger global food security. Traditional methods of risk management are often insufficient to handle the scale and complexity of modern farming challenges. Artificial Intelligence (AI) offers powerful solutions by analyzing large datasets, recognizing patterns, and generating timely recommendations for farmers. From weather forecasting and soil monitoring to pest detection and precision farming, AI-based tools are enabling proactive decision-making and reducing the likelihood of crop losses. This chapter explores the causes of crop failure, explains how AI applications are being deployed in agriculture, and highlights real-world case studies. It also examines the advantages, challenges, and future prospects of AI in farming.

**Keywords:** Artificial Intelligence, Crop Failure, Smart Farming, Decision Support, Sustainable Agriculture, Food Security

**Introduction:**

Farming has always been exposed to risks. For centuries, farmers have relied on experience, observation, and intuition to make decisions about sowing, irrigation, and harvesting. However, with climate change increasing the frequency of droughts, floods, and erratic rainfall, such traditional methods are no longer sufficient.

Crop failure—defined as a significant reduction or total loss in expected yield—has devastating consequences. It not only impacts farmers' livelihoods but also destabilizes national economies and threatens global food security. For instance, the 2022 heatwaves in Europe reduced wheat and maize yields drastically, while in India, unseasonal rains have repeatedly damaged standing crops like wheat, mustard, and pulses.

In this scenario, Artificial Intelligence (AI) emerges as a ray of hope. AI refers to the ability of computer systems to perform tasks that normally require human intelligence, such as learning, reasoning, and decision-making. By leveraging big data, machine learning, computer vision, and predictive analytics, AI provides farmers with early warnings, accurate insights, and timely recommendations. Unlike traditional advisory services, AI can process millions of data points—ranging from satellite images to soil nutrient readings—and provide customized solutions for each farm.

**Understanding Crop Failure**

Crop failure is rarely caused by a single factor; rather, it results from the interaction of multiple stresses. Some of the common causes are:

1. **Climatic Factors:**
   - Droughts, floods, cyclones, and unseasonal rainfall directly damage crops.
   - Rising global temperatures increase heat stress and shorten crop cycles.
2. **Soil-Related Issues:**
   - Continuous use of chemical fertilizers leads to soil nutrient imbalance.
   - Problems such as salinity, erosion, and waterlogging reduce productivity.
3. **Pest and Disease Infestation:**
   - Locust attacks, bacterial blight, or fungal rust can cause sudden crop collapse.
   - Early detection is difficult with manual scouting, especially in large fields.
4. **Management Errors:**
   - Poor seed selection, untimely sowing, over- or under-irrigation, and excessive pesticide use often reduce yields.

These problems are difficult to tackle with traditional methods because they require fast, data-driven decision-making. AI is designed to handle precisely this complexity.

**Table 1: Major Causes of Crop Failure and Their AI-Based Solutions**

| Cause of Crop Failure | Traditional Limitation | AI-Based Solution | Example Application |
|---|---|---|---|
| Erratic weather (drought, floods, heatwaves) | General weather forecasts are not location-specific | AI-driven localized weather forecasting | Microsoft AI Sowing App (India) |
| Soil nutrient imbalance | Soil testing is time-consuming and infrequent | AI soil sensors + predictive nutrient models | Smart soil monitoring systems |
| Pest & disease outbreak | Manual scouting is slow, labor-intensive | Computer vision & image recognition | Plantix App, Drone-based scouting |
| Inefficient resource use (water, fertilizer) | Overuse or underuse reduces yield | Precision agriculture with AI-enabled drones & IoT | Blue River "See & Spray" |
| Wrong management decisions | Reliance on experience only | AI decision-support platforms & chatbots | IBM Watson Agriculture |

**Role of Artificial Intelligence in Mitigating Crop Failure**

**1. AI in Weather Forecasting**

Weather variability is a major driver of crop losses. Traditional weather forecasts provide general information, but farmers need highly localized predictions.

- AI models use machine learning to analyze satellite data, radar inputs, and historical weather records.
- They generate farm-level forecasts that predict rainfall, temperature fluctuations, or drought conditions with higher accuracy.
- Example: AI systems can warn farmers of a possible hailstorm a few days in advance, allowing them to cover or harvest vulnerable crops early.

**Impact:** Farmers reduce losses by making informed decisions on sowing dates, irrigation scheduling, and harvesting.

**2. Soil Health Monitoring**

Healthy soils ensure resilient crops. Poor soil fertility, however, often results in low productivity and crop failure.

- AI-powered sensors (placed in fields) continuously monitor soil moisture, pH, salinity, and nutrient levels.
- Algorithms recommend the optimal fertilizer dose and irrigation schedule for each field.
- Smartphone-based AI apps allow farmers to upload soil test reports and receive instant nutrient management advice.

**Impact:** Prevents yield losses due to nutrient deficiencies and reduces unnecessary fertilizer expenses.

**3. Pest and Disease Detection**

Pests and diseases are among the fastest-spreading causes of crop failure. Manual scouting is labor-intensive and often too late.

- AI models based on computer vision can identify diseases from leaf images captured by smartphones or drones.
- Farmers get real-time alerts about pest infestations (like bollworm in cotton or blast in rice).
- AI also predicts outbreak hotspots by analyzing weather patterns, crop density, and pest life cycles.

**Impact:** Early detection means timely action with minimal pesticide use, reducing both crop losses and environmental harm.

**4. Precision Agriculture**

Precision agriculture is all about "doing the right thing at the right place and time."

- Drones equipped with AI cameras detect stressed zones in fields.

- Irrigation is optimized so that only the dry patches receive water, saving water and preventing drought stress.
- Fertilizers and pesticides are applied in variable rates, avoiding wastage and ensuring healthy crop growth.

**Impact:** Improves efficiency, reduces costs, and minimizes risk of crop failure from resource mismanagement.

**5. Predictive Analytics for Yield and Risk Management**

AI can combine climate, soil, and crop data to predict crop yields and highlight risks.

- Farmers get a realistic expectation of their harvest.
- AI systems can suggest which crop variety is best suited for the upcoming season.
- Governments and insurance companies use predictive models to design crop insurance schemes, protecting farmers from financial loss.

**Impact:** Reduces uncertainty and ensures better preparedness for unfavorable seasons.

**6. Decision-Support Systems**

AI-based platforms act like virtual advisors for farmers.

- Mobile apps (like Plantix, AgroStar) allow farmers to ask questions in local languages and get AI-generated responses.
- Some apps use chatbots to provide step-by-step guidance on sowing, irrigation, and pest control.
- Farmers benefit from 24/7 advisory support, unlike traditional extension services which are limited.

**Impact:** Helps farmers make informed decisions and prevents management-related crop failures.

**Case Examples of AI in Action**

AI is not just a concept; it is already being applied in real farming systems worldwide. Some noteworthy examples include:

1. **Microsoft AI Sowing App (India):**
   - Developed in partnership with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).
   - Farmers receive text messages advising them on the best time to sow crops like groundnut and cotton, based on soil moisture and weather forecasts analyzed by AI.
   - Results showed yield improvements of up to 30%, simply because sowing was timed correctly, reducing the risk of crop failure due to late planting or drought.
2. **Plantix Mobile App:**
   - A popular AI-based app used across Asia and Africa.
   - Farmers take photos of diseased plants, and the app uses image recognition algorithms to diagnose over 300 plant diseases, pests, and nutrient deficiencies.

- It not only provides a diagnosis but also suggests organic or chemical remedies. This helps in early intervention, preventing widespread crop damage.

3. **IBM Watson Decision Platform for Agriculture (Global):**
   - Combines weather, soil, satellite, and IoT sensor data.
   - AI processes this data to give farmers personalized recommendations on irrigation, planting dates, and harvesting.
   - Example: In Kenya, tea farmers use this platform to plan irrigation schedules more efficiently, protecting crops from drought-related stress.
4. **Blue River Technology – See & Spray (USA):**
   - Developed by John Deere's subsidiary.
   - Uses computer vision and machine learning mounted on tractors to distinguish between crops and weeds.
   - The system sprays herbicide only on weeds, reducing chemical usage by up to **90%** while preventing accidental crop damage.
5. **e-Choupal (India, with AI upgrades):**
   - Initially started as an internet-based farmer advisory system.
   - Now AI-powered, it helps farmers choose the right crop, provides localized weather alerts, and offers access to markets.
   - Farmers benefit from better planning, reduced risks, and improved profitability.

These examples show that AI is not limited to laboratories or research—it is already saving crops and livelihoods in the real world.

**Advantages of AI in Preventing Crop Failure**

AI offers a wide range of benefits that directly contribute to reducing crop losses. The main advantages include:

1. **Early Warning Systems:**
   - AI predicts risks such as pest infestations, nutrient deficiencies, or weather extremes before they become severe.
   - This allows farmers to act in advance, reducing losses dramatically.
2. **Precision and Accuracy:**
   - Unlike traditional blanket recommendations, AI provides field-specific solutions.
   - Example: Fertilizer recommendations vary even within one field, ensuring no patch is under- or over-supplied.
3. **Resource Optimization:**
   - AI minimizes wastage of water, fertilizers, and pesticides by applying them only where needed.
   - This reduces both input costs and the environmental footprint.

4. **Cost Savings for Farmers:**
    - By reducing crop losses and input costs, AI increases the profitability of farming.
    - Even smallholder farmers benefit through low-cost mobile applications.
5. **Sustainability and Environmental Protection:**
    - Reduced chemical usage helps maintain soil health and biodiversity.
    - Precision irrigation prevents groundwater overuse.
6. **Accessibility Through Digital Tools:**
    - AI-powered mobile apps bring expert knowledge directly to farmers' phones, overcoming the shortage of agricultural extension workers.

In summary, AI empowers farmers with knowledge, precision, and foresight, which together make crop failure far less likely.

**Challenges in Adopting AI in Agriculture**

Despite its promise, AI adoption in agriculture faces several barriers:

1. **High Initial Costs:**
    - Advanced technologies such as drones, AI-enabled tractors, and IoT sensors are expensive.
    - Smallholder farmers, especially in developing countries, may find it difficult to afford them.
2. **Digital Divide and Literacy Issues:**
    - Many rural farmers still lack smartphones or reliable internet access.
    - Even when apps are available, some farmers may find them difficult to use due to limited digital literacy.
3. **Connectivity Problems:**
    - Rural areas often suffer from weak network coverage, limiting access to real-time AI-based services.
    - Without proper internet infrastructure, cloud-based AI platforms cannot function effectively.
4. **Data Privacy and Ownership Concerns:**
    - AI systems rely on large amounts of farm data. Farmers are often unsure who owns this data and how it might be used.
    - Concerns about misuse of data or unfair control by large corporations create mistrust.
5. **Localization and Customization of AI Models:**
    - Many AI tools are designed in Western countries and may not account for local crop varieties, soil types, or languages.
    - Without localization, recommendations may not be fully effective.

6. **Resistance to Change:**
   - Some farmers prefer traditional methods and may be hesitant to trust new technologies.
   - Training and awareness campaigns are needed to build confidence.

These challenges highlight the need for affordable, localized, and user-friendly AI solutions, along with supportive policies and farmer education.

**Table 2: Advantages and Challenges of AI in Preventing Crop Failure**

| Advantages | Challenges |
|---|---|
| Early detection of risks | High initial investment in AI tools |
| Field-specific, customized recommendations | Limited internet access in rural areas |
| Efficient use of water, fertilizers, and pesticides | Low digital literacy among farmers |
| Cost savings with higher productivity | Data privacy and ownership concerns |
| Supports sustainable farming practices | AI models not localized for all crops & languages |

**Future Prospects**

The future of AI in agriculture is highly promising, with rapid advancements expected in the coming years:

1. **AI + Robotics for Autonomous Farming:**
   - Robots powered by AI will carry out weeding, spraying, harvesting, and even planting.
   - Autonomous machines will reduce labor dependency and improve precision.
2. **Affordable and Scalable AI Solutions:**
   - With cheaper sensors, smartphones, and better rural internet, AI will become accessible even to smallholder farmers.
   - AI advisory apps may be available in all major regional languages, ensuring inclusivity.
3. **Integration with IoT and Big Data:**
   - AI will integrate data from drones, satellites, soil sensors, and weather stations in real time.
   - This will create a digital twin of farms, allowing farmers to simulate and predict outcomes before acting.
4. **AI-Enabled Crop Breeding:**
   - AI can speed up the development of climate-resilient crop varieties by analyzing genetic data.
   - This will help produce crops resistant to drought, heat, and diseases.

5. **AI + Blockchain for Supply Chain Transparency:**
   - Blockchain combined with AI will ensure food traceability from farm to fork.
   - Farmers will gain better prices, and consumers will benefit from safe, reliable food.
6. **Policy and Institutional Support:**
   - Governments and NGOs are increasingly recognizing the value of AI.
   - Subsidies for digital farming tools, rural connectivity projects, and training programs will expand AI adoption.

In the long run, AI has the potential to transform agriculture into a climate-smart, data-driven, and highly resilient system, making crop failure a much rarer event.

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# NANOTECHNOLOGY IN AGRICULTURE

**Vijay Kumar Singh[1] and Sumit Gahlot[2]**
Department of Soil Science, (SAS)
Shri Guru Ram Rai University Dehradun (248001), Uttarakhand India.
*Corresponding author E-mail: vijaysingh24285@gmail.com, sumitgahlot53@gmail.com

**Abstract:**

Nanotechnology, the manipulation of matter at the nanoscale, is rapidly emerging as a transformative tool in modern agriculture. By exploiting the unique properties of nanoparticles, such as high surface area, reactivity, and controlled release, nanotechnology provides innovative solutions for enhancing crop productivity, soil fertility, and resource use efficiency. Applications in the form of nano-fertilizers, nano-pesticides, nano-sensors, and smart packaging are paving the way for more precise and eco-friendly farming practices. In the Indian context, where agriculture is characterized by small landholdings, overdependence on chemical inputs, and declining soil health, nanotechnology holds special significance. It can reduce fertilizer losses, lower production costs, and minimize environmental pollution while improving yields and food quality. Methods of application, including seed treatments, foliar sprays, soil incorporation, and encapsulated formulations, demonstrate the versatility of nano-products in addressing multiple agricultural challenges. This chapter discusses the scope and importance of nanotechnology in Indian agriculture, highlights its benefits such as sustainability and cost-effectiveness, and examines limitations including high costs, regulatory gaps, and potential environmental concerns. By integrating nanotechnology with existing practices, Indian agriculture can transition toward a more resilient, resource-smart, and sustainable farming system capable of meeting future food security needs.

**Introduction:**

Agriculture is the cornerstone of India's economy and cultural heritage, providing food security, raw materials, employment, and livelihoods for more than 50% of its population. It contributes around 18–20% to the national GDP and remains critical to rural development and poverty reduction. Despite its vital role, the sector faces multiple challenges in the 21st century. Stagnating crop yields, declining soil fertility, land degradation, erratic rainfall patterns, groundwater depletion, pest resistance, and overdependence on chemical inputs have combined to create a situation of ecological and economic stress. Climate change further exacerbates these vulnerabilities, threatening the sustainability of food systems in a country expected to feed nearly 1.6 billion people by 2050 (FAO, 2021). The Green Revolution of the 1960s and 1970s ushered in a phase of remarkable growth through high-yielding varieties, irrigation expansion, and intensive use of fertilizers and pesticides. While it ensured food self-sufficiency, its unintended consequences included soil degradation, loss of biodiversity, declining nutrient-use efficiency, and contamination of water bodies due to agrochemical runoff (Prasad *et al.,* 2014). Conventional methods—though valuable—are no longer adequate to address these complex challenges sustainably. There is an urgent need for innovative approaches that simultaneously enhance productivity, conserve natural resources, and minimize environmental footprints. Nanotechnology has emerged as a transformative frontier in this regard. Defined as the science and engineering of manipulating matter at dimensions between 1 and 100 nanometers, nanotechnology exploits unique physicochemical properties that differ fundamentally from bulk materials. At the nanoscale, particles exhibit high surface area, greater reactivity, enhanced solubility, and novel controlled-release behaviors. These properties can be harnessed in agriculture to revolutionize the delivery of inputs, precision monitoring, and management of natural resources (Rai & Ingle, 2012). In practical terms, nanotechnology has wide-ranging agricultural applications. Nano-fertilizers can increase nutrient-use efficiency by ensuring slow and targeted release, thereby reducing losses due to leaching, volatilization, and fixation. Nano-pesticides, often encapsulated in biodegradable carriers, provide more precise pest and disease control while lowering residue levels in food and the environment. Nanotechnology-based sensors enable real-time monitoring of soil moisture, nutrient availability, and plant health, aligning with the goals of precision farming. Post-harvest, nano-packaging materials enhance food safety, extend shelf life, and reduce post-harvest losses, which remain a major concern in India (Servin *et al.,* 2015). For Indian agriculture, nanotechnology holds unique importance. Smallholder-dominated farming systems require cost-effective, resource-efficient, and environmentally friendly technologies. The adoption of nano-fertilizers such as nano-urea developed by the Indian Farmers Fertiliser Cooperative Limited (IFFCO) demonstrates how nanotechnology can reduce dependency on conventional fertilizers and cut input costs for farmers. Similarly, research institutions such as the Indian Council of Agricultural Research (ICAR) and leading agricultural universities are actively investigating nano-based interventions for soil health improvement, water purification, and crop protection (ICAR, 2020). Thus, nanotechnology provides not only a scientific breakthrough but also a strategic opportunity for India to address its pressing agricultural challenges. By integrating nanoscale innovations into farming practices, India can advance toward climate-smart, resource-efficient, and sustainable agriculture. This chapter explores the scope, applications, benefits, and limitations of nanotechnology in agriculture, with a special emphasis on its transformative potential for the Indian farming system.

**What is Nanotechnology**

Nanotechnology is defined as the science, engineering, and application of materials and systems at the nanoscale, typically between 1 and 100 nanometers (nm). To put this into perspective, one nanometer is one-billionth of a meter—about 100,000 times smaller than the diameter of a human hair. At such a tiny scale, materials behave differently compared to their bulk form because their surface area-to-volume ratio increases dramatically, and their quantum effects start to dominate. According to the National Nanotechnology Initiative (2020), nanotechnology involves the understanding, manipulation, and control of matter at the nanoscale to exploit novel properties that emerge only at this dimension. These properties include:

- Increased strength and durability (e.g., nano-coatings).
- Enhanced solubility and reactivity (important for fertilizers and pesticides).
- Controlled release mechanisms (slow and targeted delivery of nutrients).
- Improved sensing capability (detecting changes in soil or crop health at molecular levels).

In agriculture, nanotechnology offers innovative solutions such as nano-fertilizers that release nutrients in a controlled manner, nano-pesticides that reduce chemical residues, and nano-sensors that enable precision farming. Such advancements are vital for addressing the challenges of soil degradation, nutrient losses, and environmental pollution while ensuring higher productivity and sustainability.

**Definition**

Nanotechnology is the understanding, manipulation, and application of matter at dimensions between 1–100 nanometers, where unique physical, chemical, and biological properties emerge that can be applied across multiple sectors, including agriculture.

**Applications in Agriculture**

The use of nanotechnology in agriculture has gained global attention for its potential to address long-standing challenges in productivity, resource efficiency, and sustainability. Unlike conventional agricultural inputs that often suffer from low efficiency and high losses, nanotechnology-based innovations offer precision and control at the molecular level.

Nano-fertilizers are designed to deliver nutrients in a controlled and sustained manner, thereby minimizing losses through leaching, volatilization, or fixation in the soil. Compared to conventional fertilizers, nano-fertilizers exhibit higher solubility, faster absorption, and greater bioavailability, ultimately improving nutrient use efficiency. For example, the Indian Farmers Fertiliser Cooperative Limited (IFFCO) introduced Nano Urea, which requires only 500 mL per acre compared to 45 kg of conventional urea, drastically reducing input costs for smallholder farmers while enhancing soil and water health (IFFCO, 2021).

Nano-pesticides represent another promising application. By using nano-encapsulation and slow-release mechanisms, these formulations deliver active ingredients directly to pests and pathogens with high precision. This reduces the frequency of spraying, minimizes residues in food products, and mitigates environmental contamination. In India, where pesticide overuse is a major food safety concern, nano-pesticides offer a safer and more eco-friendly alternative (Servin *et al.,* 2015). Nanotechnology has also advanced the development of sensors and nanosensors for real-time monitoring of soil health, nutrient status, water availability, and plant stress. Such tools are essential for precision farming, allowing farmers to make data-driven decisions and apply inputs only when and where needed. This reduces wastage and supports sustainable intensification of agriculture. Post-harvest, nanocomposite-based packaging materials play a vital role in extending the shelf life of perishable commodities such as fruits, vegetables, and dairy products. These materials often incorporate antimicrobial nanoparticles that inhibit microbial growth, delay spoilage, and reduce post-harvest losses. In India, where post-harvest losses account for nearly 20–25% of fresh produce, such innovations can significantly improve food availability and farmers' incomes (FAO, 2021). Additionally, nanotechnology is being explored in water purification and soil remediation through the use of nanomaterials such as nano-iron and nano-clays that remove heavy metals, pesticides, and other contaminants, ensuring cleaner irrigation water and healthier soils.

**Table 1: Applications of Nanotechnology in Agriculture**

| Application Area | Nanotechnology Innovation | Function/Benefit | Example/Reference |
|---|---|---|---|
| **Nano-fertilizers** | Nano-urea, nano-zinc, nano-iron formulations | Controlled and efficient nutrient release; reduces leaching and volatilization losses | IFFCO Nano Urea (India), Rai & Ingle, 2012 |
| **Nano-pesticides** | Encapsulated nano-pesticides, nano-herbicides | Targeted pest control; reduced chemical residues; eco-friendly | Servin *et al.,* 2015 |
| **Nano-sensors** | Soil and crop nanosensors, biosensors | Real-time monitoring of soil nutrients, water stress, and plant health | Precision farming tools, ICAR (2020) |
| **Post-harvest packaging** | Nanocomposites, antimicrobial nanoparticle coatings | Extends shelf life, reduces microbial spoilage and food loss | FAO, 2021 |
| **Water purification** | Nano-iron, nano-clays, carbon nanotubes | Removes heavy metals, pesticides, and pathogens from irrigation water | Prasad *et al.,* 2014 |
| **Soil remediation** | Nano-adsorbents and catalytic nanoparticles | Degradation of pollutants; restoration of soil health | ICAR & research consortia in India |

**Application of Nano-Products**

Nano-products in agriculture can be applied in multiple ways, each offering specific advantages in enhancing crop growth, nutrient efficiency, and environmental sustainability. Their unique properties, such as high surface reactivity, solubility, and controlled release mechanisms, allow them to be delivered effectively through seed treatment, foliar spray, soil application, pest management, and precision monitoring systems.

I. **Seed Treatment**

Seed priming or coating with nano-fertilizers, nano-zinc, or nano-silica enhances seed germination, root development, and early seedling vigor. The nanoscale particles penetrate the seed coat more efficiently, providing essential micronutrients at the earliest growth stages. For example, nano-zinc treatments have been shown to improve germination rates and chlorophyll synthesis in cereals, giving crops a competitive advantage during establishment.

II. **Foliar Application**

Foliar spraying of nano-nutrients enables rapid absorption through stomata and cuticles, effectively addressing acute nutrient deficiencies during critical growth phases. Compared to bulk fertilizers, nano-formulations require smaller quantities but provide faster and more uniform nutrient delivery. For instance, IFFCO Nano Urea applied as a foliar spray has demonstrated higher nitrogen-use efficiency and yield improvement in rice and wheat under Indian field trials.

III. **Soil Application**

Incorporating nano-fertilizers into the soil ensures slow and controlled nutrient release over extended periods. Nanoparticles such as nano-hydroxyapatite (a phosphorus carrier) or nano-clay composites reduce leaching and volatilization losses, thus improving nutrient-use efficiency and reducing groundwater contamination. This method is especially important for rainfed Indian soils where nutrient losses are high.

IV. **Nano-Pesticides**

Nano-pesticides can be applied through encapsulated or nanoparticle formulations that adhere better to leaf surfaces and resist degradation from UV radiation or rainfall. These formulations allow for slow and sustained release of active ingredients, reducing the need for repeated applications. This not only lowers the dosage but also minimizes chemical residues in food and soil (Servin *et al.,* 2015). Such precision in pest control is crucial for smallholder farmers in India, where pesticide misuse remains a challenge.

V. **Nano-Sensors and Smart Delivery Systems**

Deploying nano-sensors in soils, irrigation systems, and crop canopies enables real-time monitoring of critical parameters such as soil pH, moisture content, and nutrient availability. Smart nano-devices can also release inputs only when triggered by specific plant or soil conditions, aligning with the principles of precision agriculture. For example, nanosensors detecting nitrogen deficiency can trigger the release of nano-urea capsules directly into the root zone, thereby maximizing efficiency and minimizing wastage.

**VI. Post-Harvest Applications**

Nano-coatings on fruits and vegetables act as protective films, reducing microbial growth, water loss, and oxidation. Edible nano-films enriched with antimicrobial nanoparticles (like silver or zinc oxide) extend shelf life without compromising food quality. In India, where post-harvest losses of perishable commodities are significant, such nano-packaging technologies hold great promise for reducing food waste and improving farmers' incomes.

**Role of Nanotechnology in Agriculture**

Nanotechnology plays a transformative role in modern agriculture by offering innovative solutions to long-standing challenges such as low input-use efficiency, declining soil fertility, pest resistance, water scarcity, and post-harvest losses. By exploiting the unique properties of materials at the nanoscale (1–100 nm), nanotechnology enhances precision, efficiency, and sustainability in agricultural practices. Its role spans from seed germination to harvest and even post-harvest management, making it a holistic tool for sustainable farming.

**I. Enhancing Nutrient Use Efficiency**

Conventional fertilizers often show nutrient-use efficiency rates of less than 40–50%, with the remainder lost through leaching, volatilization, or fixation. Nanotechnology addresses this limitation through nano-fertilizers, which release nutrients in a controlled and sustained manner. Their higher solubility and surface reactivity allow for better plant uptake at lower doses. For instance, IFFCO Nano Urea, developed in India, has been demonstrated to replace one 45 kg bag of urea with a 500 mL nano-formulation, reducing nitrogen loss, input costs, and environmental pollution (IFFCO, 2021). Similarly, nano-zinc and nano-iron fertilizers improve micronutrient efficiency, which is especially important in Indian soils that are widely deficient in zinc and iron.

**II. Sustainable Pest and Disease Management**

Nano-pesticides and nano-herbicides ensure precise delivery of active ingredients to target pests and pathogens. By encapsulating pesticides within nanoparticles or nanoemulsions, these formulations enable slow release, UV protection, and higher adherence to plant surfaces. This reduces application frequency and chemical residues in soil and food (Servin *et al.,* 2015). In India, where pesticide misuse has caused ecological imbalance and health hazards, nano-pesticides provide a safer, more eco-friendly alternative. For example, chitosan-based nanopesticides not only control pests but also act as biostimulants, enhancing plant immunity.

**III. Advancing Precision Agriculture**

Nanotechnology plays a critical role in precision farming through the use of nanosensors and smart devices. These sensors can detect soil pH, nutrient levels, water stress, and even early signs of plant disease at very low concentrations. Farmers can then apply the right inputs at the right time and in the right amounts. This is particularly valuable for Indian smallholder farmers who operate on marginal lands and must optimize resource use. Research institutions like ICAR have initiated programs to test nano-sensors for monitoring nitrogen status in soils, which can reduce unnecessary fertilizer use.

**IV. Improving Post-Harvest Management**

In India, nearly 20–25% of fresh produce is lost post-harvest due to spoilage. Nanotechnology provides effective solutions through nanocomposite-based packaging materials and edible nano-coatings. Packaging infused with silver, zinc oxide, or titanium dioxide nanoparticles has antimicrobial properties that delay spoilage. Edible nano-films, applied to fruits and vegetables, reduce moisture loss and oxidation. Such innovations not only extend shelf life but also improve market access for farmers by reducing losses during transport and storage (FAO, 2021).

**V. Environmental Remediation and Water Management**

Nanotechnology is increasingly used in soil and water cleanup, which is crucial for areas affected by pollution and degradation. Nano-iron particles are effective in removing arsenic, chromium, and pesticide residues from contaminated soils and groundwater. Similarly, carbon nanotubes and nano-clays adsorb pollutants and improve water quality for irrigation. Given India's widespread groundwater contamination by fluoride and heavy metals, nanotechnology-based purification systems can ensure safer water for both crops and human consumption.

**VI. Climate-Smart Agriculture**

Nanotechnology contributes directly to climate-smart farming systems. By improving nutrient-use efficiency, it reduces greenhouse gas emissions such as nitrous oxide from excess nitrogen fertilizer. Nano-enabled inputs require smaller doses, lowering the carbon footprint of agriculture. Additionally, nano-coatings can enhance drought tolerance by improving water retention in soils and seeds. Such strategies are vital for India, where agriculture is highly vulnerable to erratic rainfall and climate change.

**VII. Enhancing Food Quality and Safety**

Beyond the field, nanotechnology plays a role in improving food quality. Nano-biosensors can detect pathogens, toxins, and pesticide residues in food products, ensuring safety for consumers. In India, where food contamination remains a public health issue, such technologies can strengthen food monitoring systems. Nano-additives are also being developed to fortify foods with micronutrients like iron and zinc, addressing widespread deficiencies in rural populations.

**VIII. Smart Delivery Systems**

One of the most promising roles of nanotechnology lies in smart delivery mechanisms. Nanocapsules and nanocarriers can deliver nutrients, pesticides, or genetic material in a targeted and controlled manner, releasing them only when triggered by environmental cues such as pH, temperature, or moisture. This role aligns perfectly with the concept of sustainable intensification, as it maximizes the efficiency of every input while minimizing waste.

**Conceptual Diagram: Role of Nanotechnology in Agriculture**

**Nanotechnology**

(1–100 nanometer scale)

**Nano-Fertilizers** **Nano-Pesticides** **Nano-Sensors**

(Controlled nutrient release, efficiency) (Targeted pest controlless chemical residue)

(Soil, water, crop monitoring)

▼

**Sustainable Agriculture**

(Higher productivity • Resource efficiency • Eco-friendly)

**Explanation of the Diagram**

- Nanotechnology (1–100 nm scale): Acts as the central enabling science that manipulates matter at the nanoscale to unlock unique properties.
- Nano-Fertilizers: Enhance nutrient uptake by plants through controlled and slow release, reduce leaching and volatilization losses, and improve overall nutrient-use efficiency.
  Example: IFFCO Nano Urea in India replaces bulk urea with a few milliliters per spray, reducing costs and nitrogen losses.
- Nano-Pesticides: Deliver active ingredients in a precise and targeted manner, ensuring better pest control with minimal chemical residue in soil and food.
  Example: Encapsulated nano-pesticides reduce spraying frequency and environmental toxicity.
- Nano-Sensors: Provide real-time monitoring of soil moisture, nutrient status, and plant health, enabling precision farming and optimal input use.
  Example: Biosensors detecting nitrogen levels in Indian soils help tailor fertilizer application.
- Sustainable Agriculture Outcome: These applications collectively promote higher productivity, resource efficiency, and environmental sustainability, aligning with India's goals of climate-smart agriculture and food security.

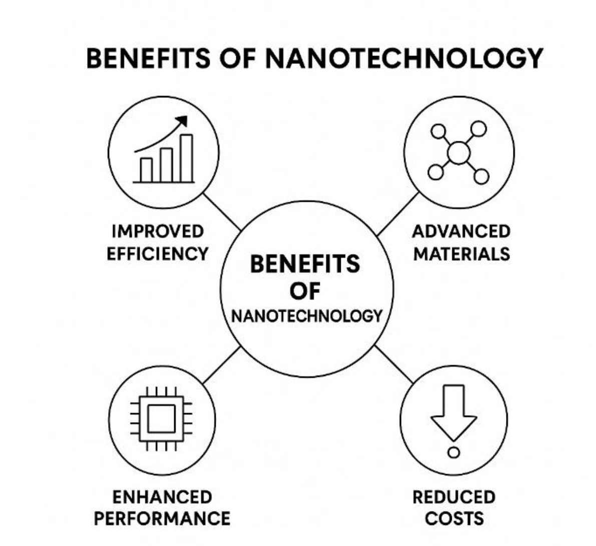
**Importance of Nanotechnology in the Indian Farming System**

India's agriculture is the backbone of its economy, employing more than half of the workforce and contributing significantly to food security. However, the system is challenged by fragmented landholdings, indiscriminate fertilizer and pesticide use, declining soil fertility, low water-use efficiency, and the impacts of climate change. In such a scenario, nanotechnology offers innovative pathways for sustainable intensification and modernization of Indian farming.

One of the most critical applications is the development of nano-fertilizers, which address the problem of low nutrient-use efficiency associated with conventional fertilizers such as urea and DAP. Over-application of these bulk fertilizers leads to soil nutrient imbalance, groundwater contamination, and greenhouse gas emissions. Studies have shown that nano-urea and nano-zinc formulations not only reduce the amount of fertilizer required but also increase nutrient uptake efficiency by plants, thereby improving yields and reducing environmental degradation (Prasad *et al.,* 2014; IFFCO, 2021). Another area of importance is nano-pesticides and nano-herbicides, which provide safer and more effective alternatives to conventional agrochemicals. These nano-enabled formulations enhance adhesion, stability, and controlled release of active compounds, reducing the frequency of spraying and minimizing pesticide residues on crops. For India, where excessive pesticide residues often lead to export rejections and food safety concerns, such innovations are vital for both domestic health and international trade (Rai & Ingle, 2012). Nano-sensors and precision agriculture tools represent another crucial role. They can monitor soil pH, nutrient status, moisture content, and even plant stress in real time, providing farmers with actionable data. This is particularly relevant for small and marginal farmers in India, who often lack access to advanced technologies. Government programs like the Digital Agriculture Mission can integrate nanosensor technologies to promote resource-smart farming practices, reducing input costs while maintaining or enhancing productivity. In addition, nanotechnology supports water-use efficiency and soil health restoration. Nanoparticles such as nano-iron, carbon nanotubes, and nano-clays are increasingly used in soil and water remediation. They help remove toxic contaminants like arsenic, fluoride, and heavy metals from irrigation water, a major concern in states like Punjab, West Bengal, and Bihar. Similarly, nanomaterials can be applied to improve soil structure, increase water-holding capacity, and enhance organic matter dynamics. Nanotechnology also plays a role in post-harvest management and value addition. India faces high post-harvest losses in fruits, vegetables, and grains, estimated at 15–25%. Nanocomposite packaging materials and edible nano-coatings can extend shelf life by preventing microbial growth and reducing spoilage, thereby improving food availability and farmer incomes. These technologies can directly benefit India’s perishable supply chains, where inadequate cold storage remains a persistent bottleneck. From a broader perspective, nanotechnology contributes to climate-smart agriculture. By reducing fertilizer and pesticide inputs, improving water efficiency, and lowering emissions, it aligns with India’s commitments under global climate agreements. Furthermore, it enhances resilience by providing stress-tolerant crop solutions and sustainable practices to cope with climate variability. Thus, the importance of nanotechnology in Indian agriculture lies not just in increasing yields, but in transforming the system toward sustainability, safety, and resilience. By improving resource efficiency, reducing environmental risks, and ensuring better marketability of produce, nanotechnology can significantly enhance farmer livelihoods while contributing to national food and nutritional security.

**Benefits and Limitations of Nanotechnology in Indian Farming**

Nanotechnology offers transformative benefits to Indian agriculture by addressing long-standing inefficiencies in input use and environmental management. One of the most promising contributions is the enhancement of nutrient use efficiency. Unlike conventional fertilizers that often suffer from significant nutrient losses through leaching, volatilization, or fixation in soil, nano-fertilizers are engineered to release nutrients in a controlled and targeted manner. This not only improves the uptake of essential nutrients by crops but also reduces the excessive use of bulk fertilizers such as urea and diammonium phosphate, which are known to degrade soil health and pollute water bodies. Similarly, nano-pesticides and nano-herbicides have emerged as advanced alternatives to traditional agrochemicals, providing site-specific delivery and sustained release of active compounds. Their application minimizes the frequency of spraying, lowers chemical residues in food, and reduces environmental contamination—issues of particular concern in India, where pesticide overuse has been a persistent problem.




Economically, nanotechnology also holds immense promise for smallholder farmers, who form the backbone of Indian agriculture. By lowering input requirements while maintaining or even increasing crop yields, nano-products can significantly reduce production costs, thereby improving farm profitability. At the same time, nanosensors designed for soil, water, and plant health monitoring are helping to usher in precision agriculture, a practice that allows farmers to make data-driven decisions on resource use. These innovations align well with national initiatives such as the Digital Agriculture Mission, which seeks to integrate advanced technologies into rural farming systems. Beyond direct economic gains, nanotechnology contributes to climate-smart agriculture by reducing greenhouse gas emissions associated with conventional fertilizer use, improving water-use efficiency, and enhancing resilience against climate-induced stresses such as drought and nutrient depletion. Taken together, these benefits position nanotechnology as a powerful tool to modernize Indian agriculture, ensuring sustainability, productivity, and food security for a growing population.

However, the application of nanotechnology in farming is not free from challenges and limitations. One of the foremost concerns is the high cost of production and commercialization of nano-based products, which restricts their accessibility for the majority of India’s resource-poor farmers. Without subsidies, public–private partnerships, or cost-sharing models, widespread adoption is likely to remain limited. Equally pressing is the issue of farmer awareness: many cultivators remain unfamiliar with nanotechnology, and India's agricultural extension services are not yet adequately equipped to train farmers on its safe and effective use. This knowledge gap risks both underutilization and potential misuse of nano-products. Furthermore, the environmental and health implications of nanoparticles remain insufficiently understood. Questions persist about their long-term persistence in soils, their interactions with beneficial soil microbiota, and the possibility of bioaccumulation in food chains. Until comprehensive, evidence-based safety assessments are conducted, concerns about unintended risks will continue to shadow their adoption.

Adding to these challenges is the absence of robust regulatory frameworks in India and globally. While some guidelines exist for nanotechnology research and product development, there is still a lack of clarity on safety testing protocols, labeling, and approval mechanisms. This regulatory vacuum creates uncertainty for innovators, industries, and farmers alike, and slows down the pace of commercialization. Finally, consumer acceptance represents a subtle yet significant limitation. Given increasing awareness about food safety, many consumers may be hesitant to embrace crops grown with nano-inputs unless transparent communication, labeling, and trust-building measures are put in place. This underlines the importance of regulatory bodies, policymakers, and research institutions working collaboratively to ensure that nanotechnology is deployed responsibly, sustainably, and in ways that benefit both farmers and consumers. In summary, nanotechnology offers an unprecedented opportunity to transform Indian agriculture by making it more resource-efficient, environmentally sustainable, and economically viable. Yet its promise can only be fully realized if parallel efforts are made to address cost barriers, build farmer capacity, establish strong regulatory frameworks, and conduct long-term safety evaluations. Only then can nanotechnology move from a frontier innovation to a mainstream agricultural practice capable of reshaping India's farming future.

**Conclusion:**

Nanotechnology stands at the frontier of agricultural innovation, offering a transformative pathway for addressing some of the most pressing challenges faced by Indian agriculture. Its ability to improve soil health, optimize nutrient delivery, and minimize environmental degradation positions it as a critical tool for sustainable farming in the 21st century. The integration of nano-fertilizers and nano-pesticides promises not only to enhance productivity but also to reduce the ecological footprint of conventional practices, aligning with global commitments toward climate-smart agriculture. Additionally, the deployment of nano-sensors and smart delivery systems can empower farmers with precision-based management, thereby reducing resource wastage and improving resilience to climate variability. However, realizing this potential requires overcoming substantial barriers. High production costs, limited farmer awareness, and the absence of robust regulatory frameworks continue to restrict its widespread implementation. Equally pressing are the concerns related to the long-term ecological and health impacts of nanoparticles, which necessitate rigorous scientific evaluation and transparent risk assessment. Addressing these challenges demands a multi-pronged approach involving policymakers, scientists, industry stakeholders, and farming communities. Strong governmental support through subsidies, awareness campaigns, and regulatory clarity will be essential to bridge the gap between laboratory research and field application. If these challenges are systematically addressed, nanotechnology could become a cornerstone of India's agricultural revolution. It has the capacity not only to restore soil fertility and safeguard food security but also to empower farmers with sustainable, cost-effective, and environmentally responsible practices. With visionary leadership, interdisciplinary collaboration, and farmer-centered policies, nanotechnology has the potential to reshape the future of Indian agriculture, making it more productive, resilient, and sustainable for generations to come.

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# SOIL ORGANIC CARBON DYNAMICS AND CARBON SEQUESTRATION IN AGRICULTURE: MANAGEMENT STRATEGIES TO ENHANCE CARBON SEQUESTRATION

**Jyothi Prakash H P*[1], Vinay Kumar M[2] and Sanjay Kumar**

[1]Department of Plant and Soil Sciences,

Mississippi State University, Starkville, Mississippi, USA – 39759

[2]Department of Agricultural Engineering,

Akshaya Institute of Technology, Tumakuru – 572106 (Karnataka), India

[3]Department of Agronomy,

University of Agricultural Sciences, Raichur – 584104 (Karnataka), India

*Corresponding author E-mail: jyothiprakash.hp@gmail.com

**Abstract:**

Soil organic carbon (SOC) plays a critical role in maintaining soil health, enhancing agricultural productivity, and mitigating climate change through carbon sequestration. The dynamic nature of SOC is influenced by a complex interplay of biological, chemical, and physical processes, as well as land-use practices and climatic conditions. Agricultural soils, in particular, hold significant potential for carbon sequestration when managed sustainably. This review explores the mechanisms of SOC dynamics and evaluates various agricultural management strategies aimed at enhancing carbon storage in soils. Key practices include conservation tillage, cover cropping, crop rotation, organic amendments, agroforestry, and integrated nutrient management. These strategies not only promote SOC stabilization but also improve soil structure, water retention, and nutrient cycling. The effectiveness of carbon sequestration is context-dependent, influenced by soil type, climate, and farming systems. Advancing monitoring tools, incentivizing carbon farming, and integrating policy frameworks are essential to scale up SOC sequestration. Enhancing SOC through sustainable agricultural practices represents a viable pathway to address global food security and climate resilience.

## I. Introduction:

Soil organic carbon (SOC) is one of the most widely use soil quality indicator. In terrestrial ecosystems, it determines the fertility and productivity by improving the physical, chemical and biological properties, and also useful in predicting climate change and its effects. Global SOC pool in the top 1 m soil is approximately 1200 to 1600 Pg (1 Pg = 1015 g) and 695 to 930 Pg of inorganic carbon. The amount of carbon (C) stored in soil is two times of the global biotic C pool and three times of the global atmospheric C pool. The concentration of atmospheric carbon dioxide ($CO_2$) may be greatly impacted with a small change in SOC pool, thus affecting the global carbon cycle. It is therefore important to preserve, maintain and store SOC while addressing problems of climate change and food insecurity. Carbon sequestration by terrestrial ecosystem is the net removal of carbon dioxide ($CO_2$) gas from the atmosphere or the avoidance of its emissions from terrestrial ecosystems into the atmosphere. The removal process include: $CO_2$ uptake from the atmosphere by green plants through photosynthesis and the carbon stored as plant biomass (in the trunks, branches, leaves and roots of the plants) and organic matter in the soil. Soil carbon sequestration involves adding the maximum possible organic carbon to the soil. The carbon dioxide gas is a major cause of the atmospheric greenhouse effect and hence can influence the global climate. Agricultural practices for enhancing SOC must either increase organic matter inputs to the soil, decrease decomposition of soil organic matter (SOM) and oxidation of SOC, or a combination of both. Soil C sequestration can improve soil quality and reduce agriculture's contribution to $CO_2$ emissions (Poeplau *et al.,* 2017).

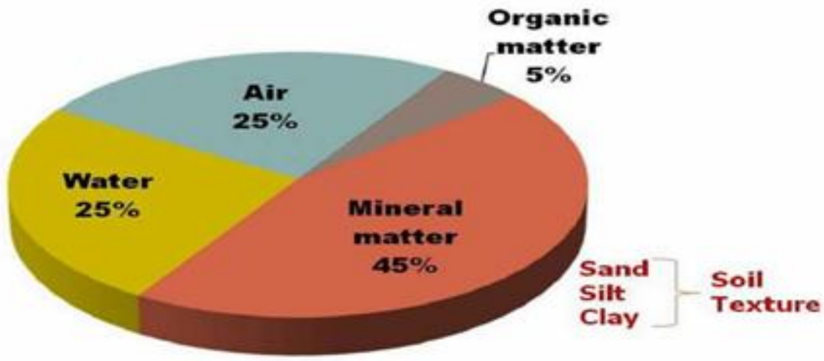



**Figure 1: Components of soil**

**Soil organic carbon**

- Soil organic carbon is a measureable component of soil organic matter.
- Organic matter makes up just 2–10% of most soil's mass and has an important role in the physical, chemical and biological function of agricultural soils.
- Soils with less than 0.5% organic C are mostly limited to desert areas.
- Soils containing greater than 12 - 18% organic carbon are generally classified as organic soils.

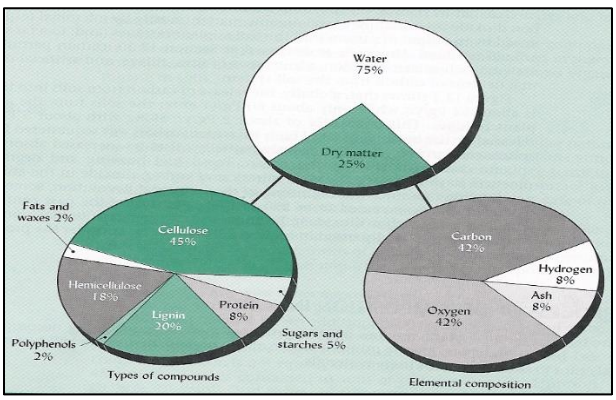



**Figure 2: Elemental and different compounds composition of plant dry matter**

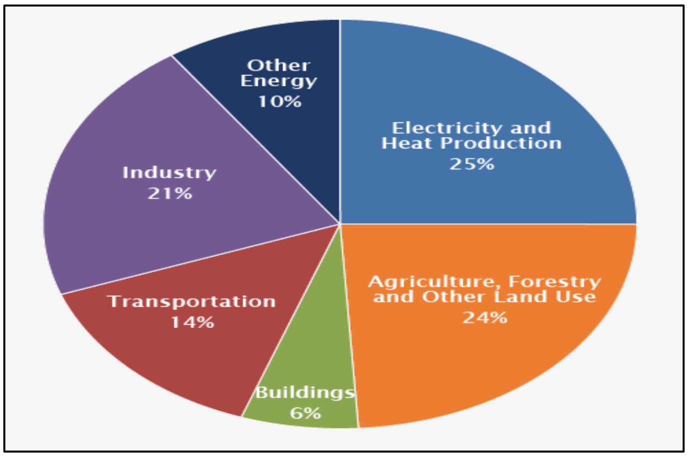



**Figure 3: Global greenhouse gas emission by different sectors**

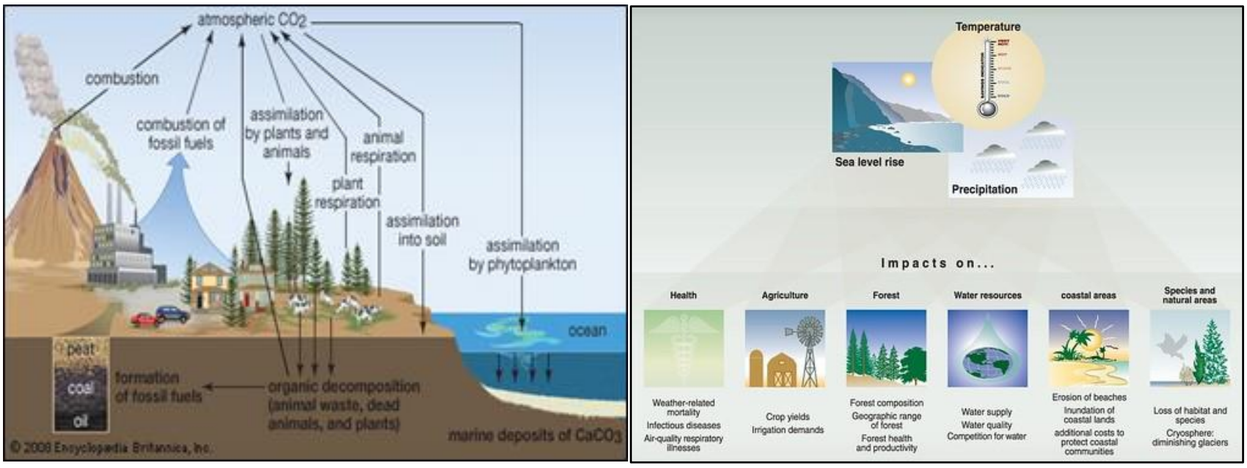



**Figure 4: Potential climate change impact**

## II. Soil Organic Carbon Dynamics

### Soil organic carbon fractions

- Total carbon, total inorganic carbon and total organic carbon
- Potassium dichromate oxidizable carbon (PDOC)
- Potassium permanganate oxidizable carbon (PPOC)
- Cold water extractable carbon
- Hot water extractable carbon
- Soil microbial biomass carbon
- Particulate organic carbon
- Water stable aggregate associated carbon
- Light fraction organic carbon
- Mineralizable organic carbon

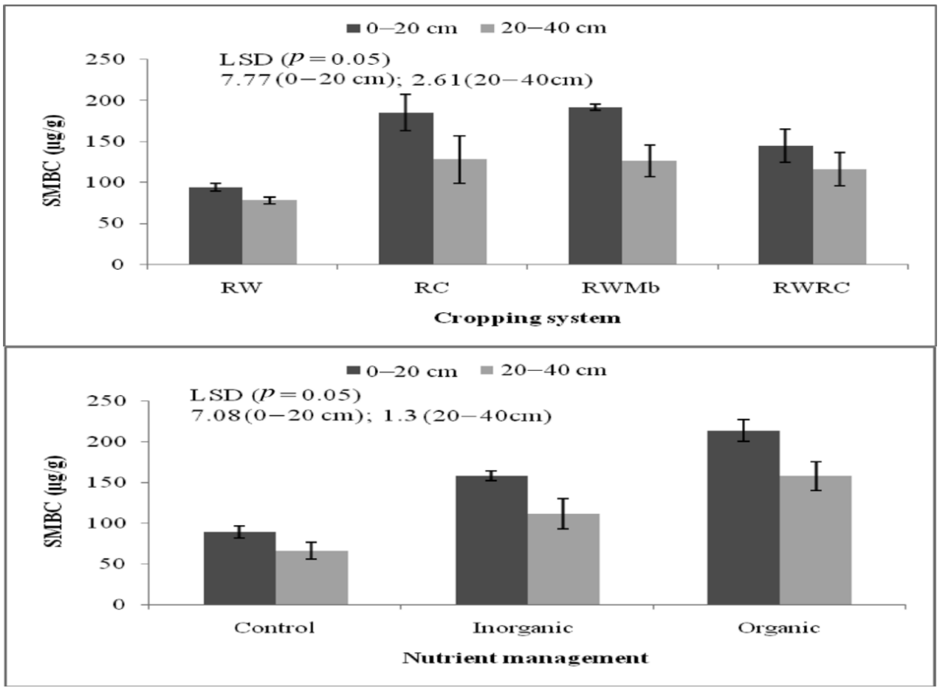



**Figure 5: Soil microbial biomass carbon (SMBC) under different cropping systems and nutrient management practices**

IIPR, Kanpur, UP Ghosh *et al.* (2003)

IARI, New Delhi Sumantha *et al.* (2013)

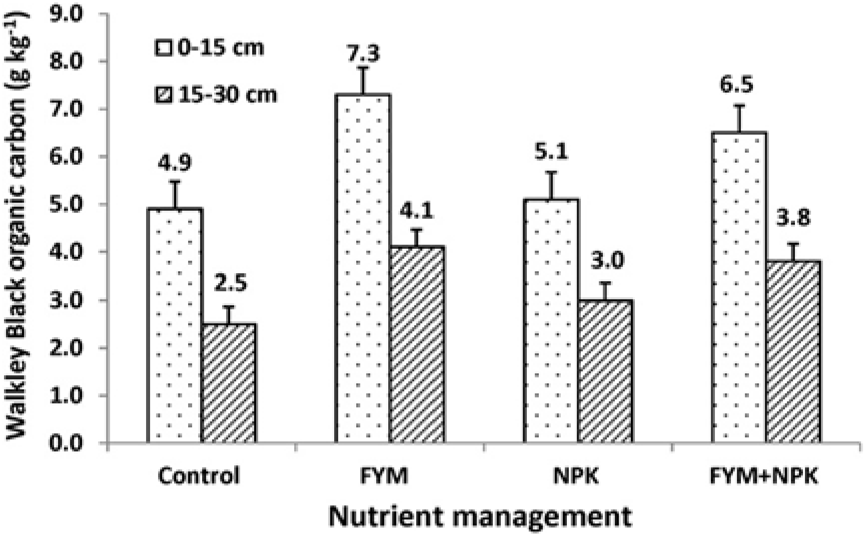



**Figure 6: Changes in Walkley and Black organic carbon as influenced by application of FYM and fertilizers after wheat grown in a 6-year-old pearl millet–wheat cropping system IARI, New Delhi Manohara *et al.* (2010)**

**III. Carbon Sequestration**

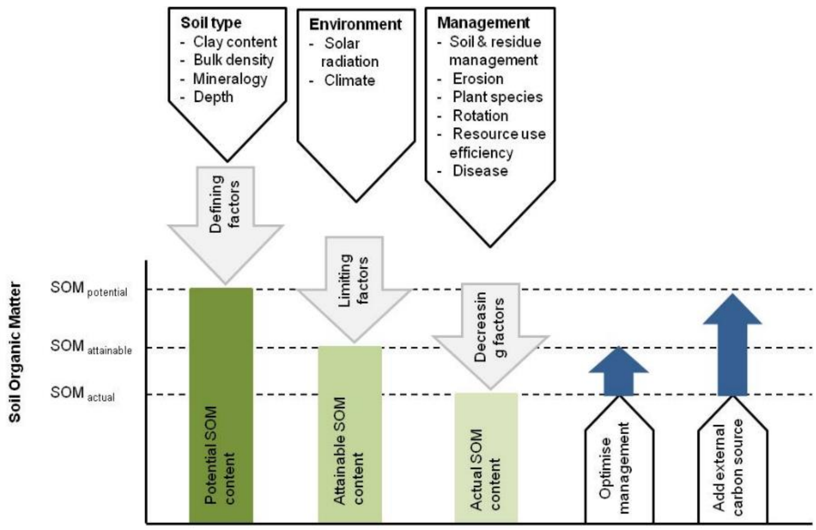
- "It refers to the provision of long-term storage of carbon in the terrestrial biosphere, underground or the oceans, so that the buildup of carbon dioxide concentration in the atmosphere will reduce or slow down". (Lal,1995)

- In other words, it also refers to the process of removing carbon from the atmosphere and depositing it in a reservoir. This carbon storages or reservoirs are also known as carbon pools.

**Types of Sequestration**

- Ocean Sequestration: Carbon stored in oceans through direct injection or fertilization.
- Geologic Sequestration: Natural pore spaces in geologic formations serve as reservoirs for long-term carbon dioxide storage.
- Terrestrial Sequestration: A large amount of carbon is stored in soils and vegetation, which are our natural carbon sinks. Increasing carbon fixation through photosynthesis, slowing down or reducing decomposition of organic matter, and changing land use practices can enhance carbon uptake in these natural sinks.
- The oceanic pool is estimated at 38,000 Pg C and is increasing at the rate of 2.3 Pg C $yr^{-1}$.
- The geological carbon pool, comprising fossil fuels, is estimated at 4,130 Pg C.
- The soil pedologic pool is estimated at 2,500 Pg to 1 m depth.
- This pool has two distinct components: soil organic carbon (SOC) pool estimated at 1550 Pg and soil inorganic carbon (SIC) pool at 950 Pg.
- The SIC pool includes elemental C and carbonate minerals such as calcite, dolomite and comprises primary and secondary carbonates.
- The fourth largest pool is the atmospheric pool comprising ~800 Pg of $CO_2$-C, and is increasing at the rate of 4.2 Pg C $yr^{-1}$ or 0.54 percent $yr^{-1}$.
- The smallest among the global carbon pools is the biotic pool, which is estimated at 620 Pg, the terrestrial and atmospheric carbon pools strongly interact with one another through photosynthesis and respiration.

**Factors influencing carbon sequestration**



**Why Carbon Sequestration is Important?**



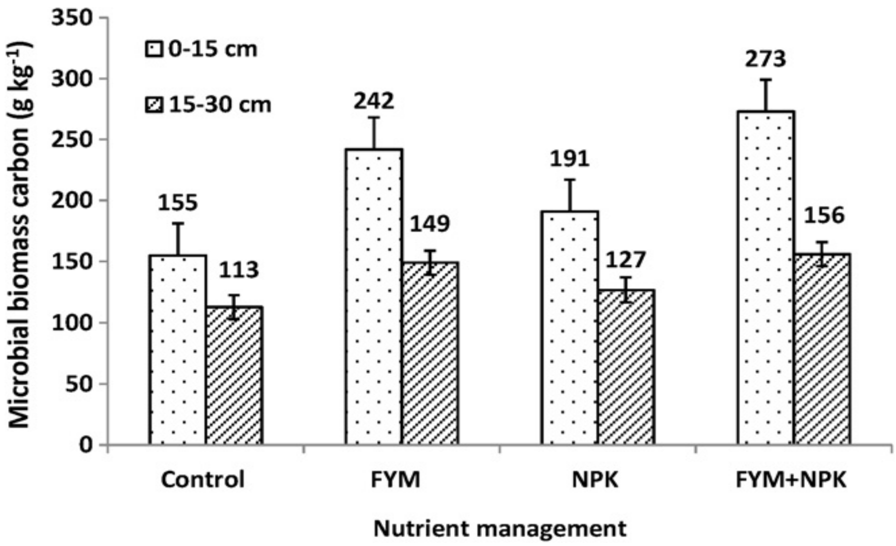



**Figure 7: Changes in microbial biomass carbon as influenced by application of FYM and fertilizers after wheat grown in a 6-year-old pearl millet–wheat cropping system IARI, New Delhi Manohara *et al.* (2010)**

**Conservation Tillage:**

- Intensive tillage causes disturbances to the soil increasing mineralization.
- No till or reduced till improve soil carbon preventing soil loss by erosion.
- Conservation tillage systems keep more crop residues on the soil surface and have a higher SOC concentration in surface layer than conventional tillage

**Nutrient management**

- Chemical fertilizers are a source of emission of GHGs, especially $N_2O$. In addition to it, fertilizer production and its transportation are also associated with the emissions of GHGs.
- Judicious use of fertilizers increases crop yields and profitability and about 50g $CO_2$ additions to the atmosphere has been contributed by the cultivated soils, through the process of mineralization of soil organic carbon .
- Nutrients in organic form are essentially required to conserve the carbon in the soil.

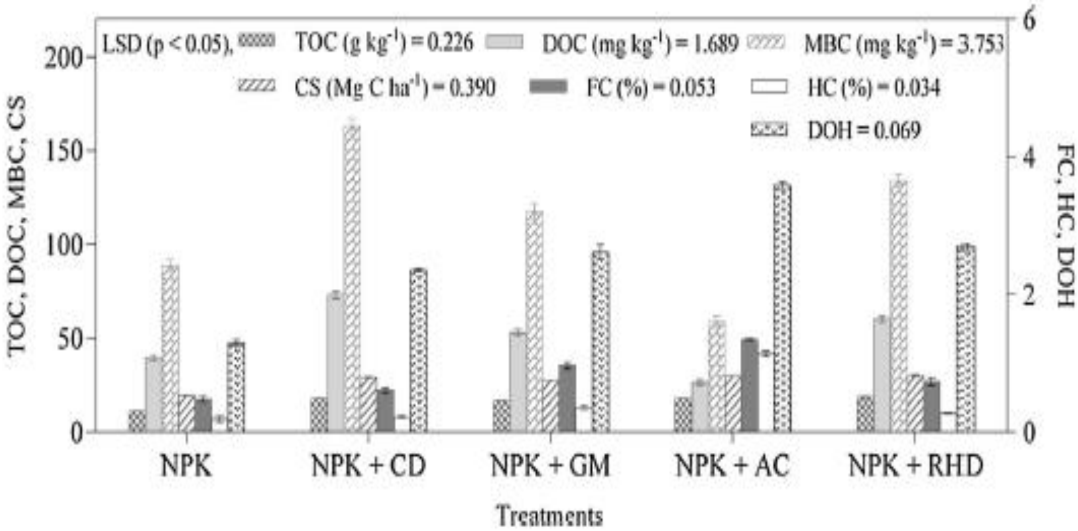



**Figure 8: Effect on soil carbon fractions at different INM practices in wheat grown in North East India**

**Agroforestry**

- Agroforestry is the combination of agriculture and forestry in which perennial trees and shrubs are grown in combination with agricultural crops.
- Planting of different kinds of trees, including orchards, fruit plants, and woodlands into the croplands, can improve soil carbon sequestration.
- Agroforestry has an enormous potential for carbon sequestration in croplands because agroforestry practices accumulate more C than forests and pastures because they have both forest and grassland sequestration and storage patterns active.
- Agricultural soils can sequester more quantities of carbon by the adoption of agroforestry.

- The carbon sequestrations potential of agroforestry systems is estimated between 12 and 228 Mg ha$^{-1}$, so on the Earth's total suitable area for crop production, a total of about 1.1–2.2 Pg C can be sequestered in the agricultural soils in the next 50 years

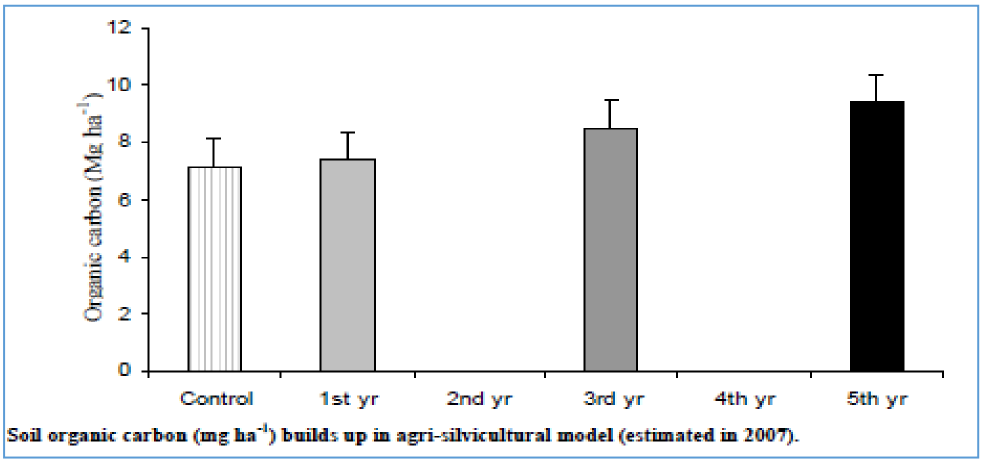



**Figure 9: Soil organic carbon (mg ha$^{-1}$) build up in agri-silviculture model PAU, Ludhiana, Punjab Chauhan *et al.* (2011)**

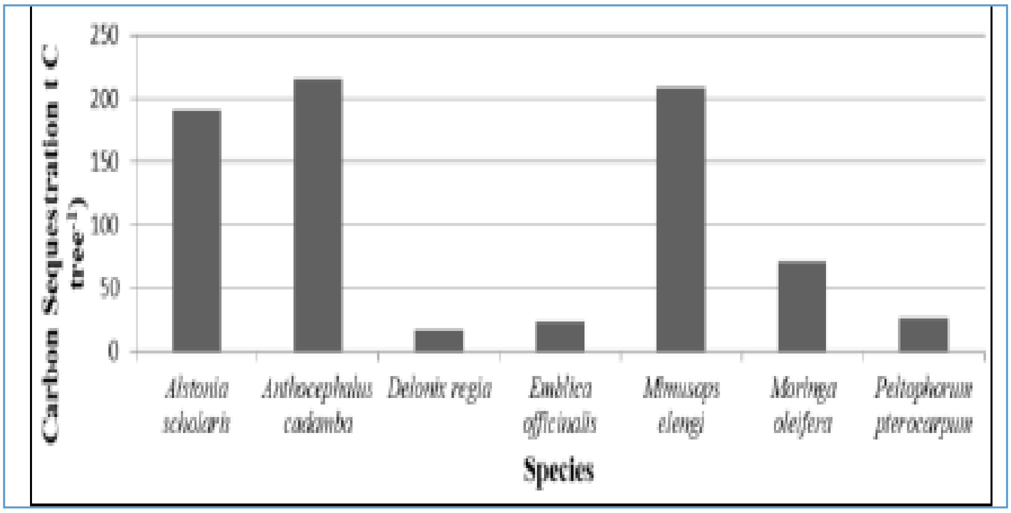
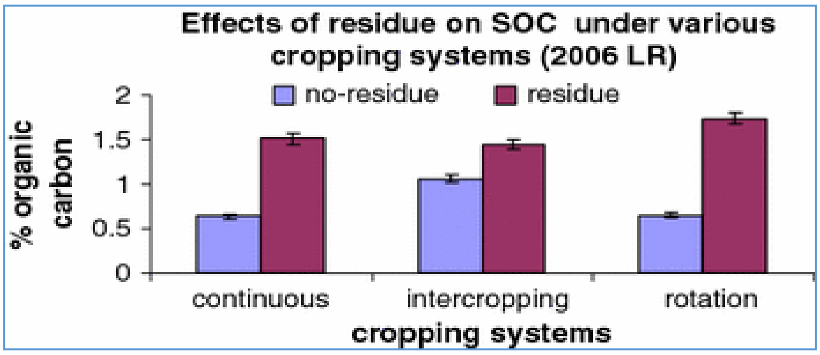



**Figure 10: Carbon sequestration of different tree species in Uttar Pradesh ARS, Allahabad, Uttar Pradesh Tanvie and Neelam (2017)**

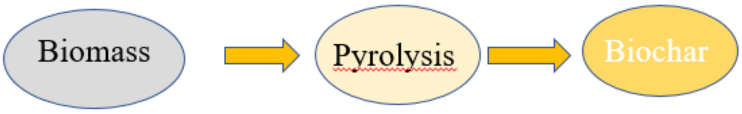
**Crop Residue Management:**

- ✓ Crop residues are completely removed for animal feed and biofuel.
- ✓ Soil carbon is obtained from the biomass of roots and dead above ground biomass.

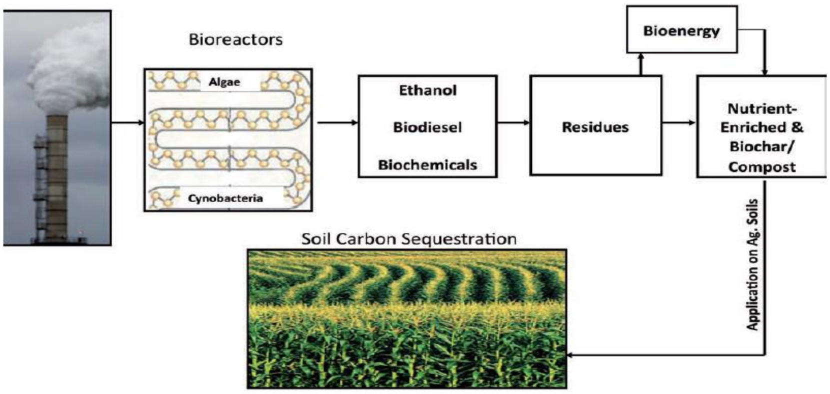


**Biochar:**

- All plant biomass and animal biomass can be converted into biochar.




- It comprises stable aromatic form of organic carbon and does not readily return to atmosphere as $CO_2$.
- Also increases soil fertility by improving soil carbon by promoting plant and root growth.
- Besides this, they also improve cation exchange capacity, water retention, aggregation and porosity.




**Cover Crops:**

- Cover crops provide a biodiversity rich soil, deep roots improve soil structure.
- They also increase the net photosynthetic activity resulting in increased carbon stock than carbon losses.
- To improve soil C
- Provide cover-reduce soil erosion
- Capture N-reduce leaching

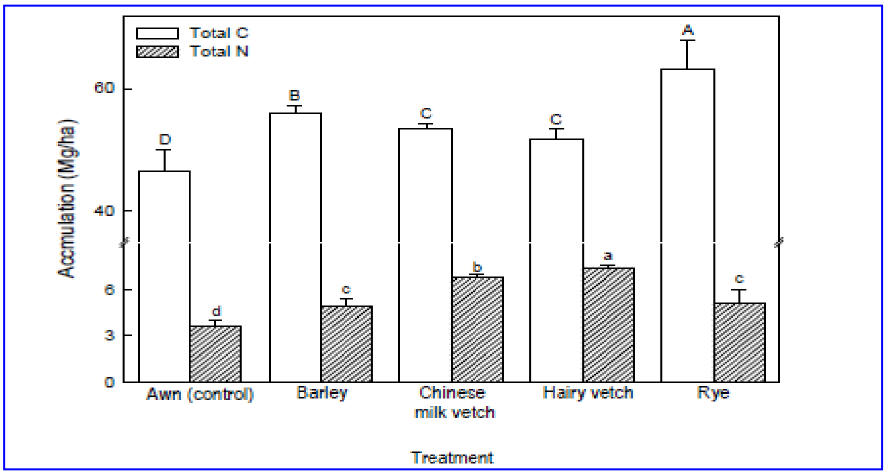



**Figure 11: Total carbon and nitrogen accumulated by selected winter crops in paddy field within 60 cm depth CoA&RS, Korea Lee *et al.* (2011)**

**Pastures and Grazing:**

- Higher root to shoot ratio than many crops.
  Grasses: 0.4-3.7, whereas in crops: 0.1
- Soils are not disturbed as in tillage conditions.
- Grazing intensity has the potential to modify the soil structure and hence the storage.
- Hence rotational grazing and set stock methods of reduced grazing, legume species in rotation should be practiced.

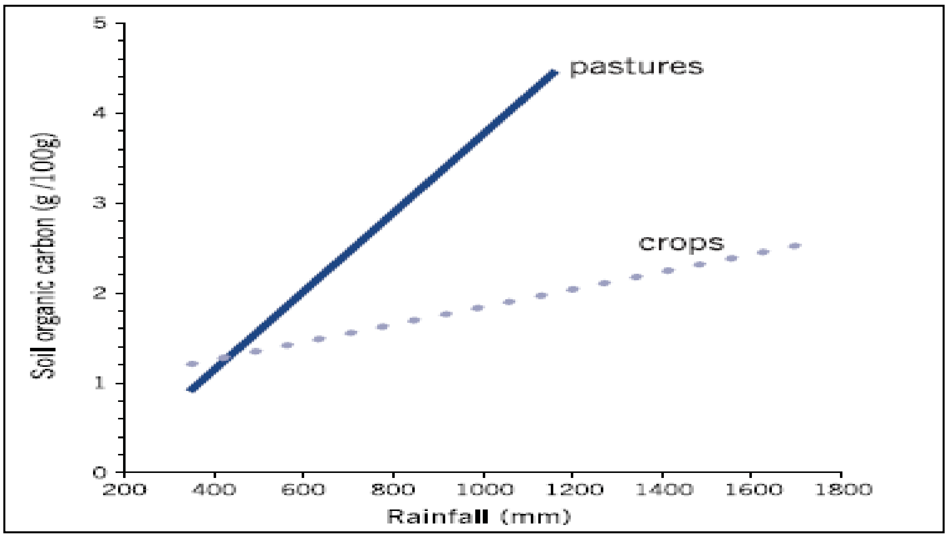



**Figure 12: Effect of pastures on soil carbon levels IGFRI, Jhansi, Uttar Pradesh Rai *et al.* (2013)**

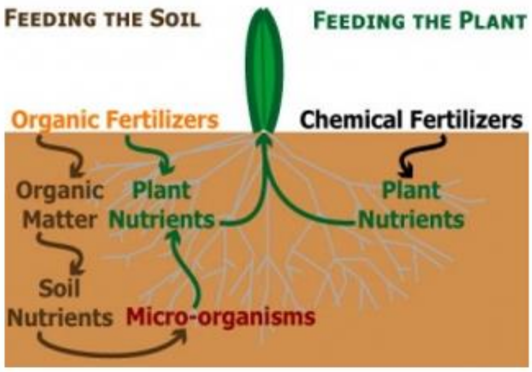
**Cropping Systems:**

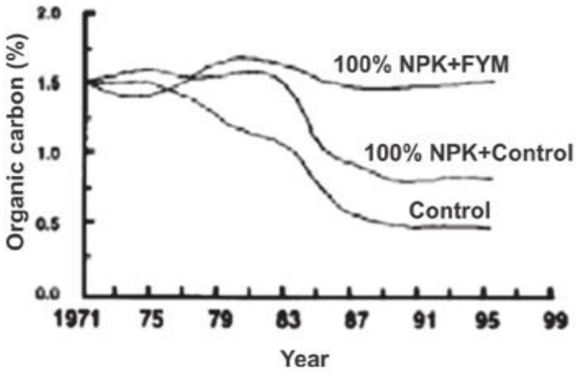
- Continuous cover- reducing fallow periods specially in summer.
- Crop Rotation- with legumes and grasses in course without leaving fallow.
- Agroforestry- Including perennials in cropping that provide a continuous addition of litter.
- For each legume crop sown, approximately 1 ton of $Co_2$ – C emission is avoided.
- There is also increased plant residue input
- And increased soil organic carbon content.

**Manuring and Composting:**

✓ Provides biomass inputs as energy source for soil microbes.

✓ They increase microbial intensity which increase the aggregate stability preventing soil erosion.



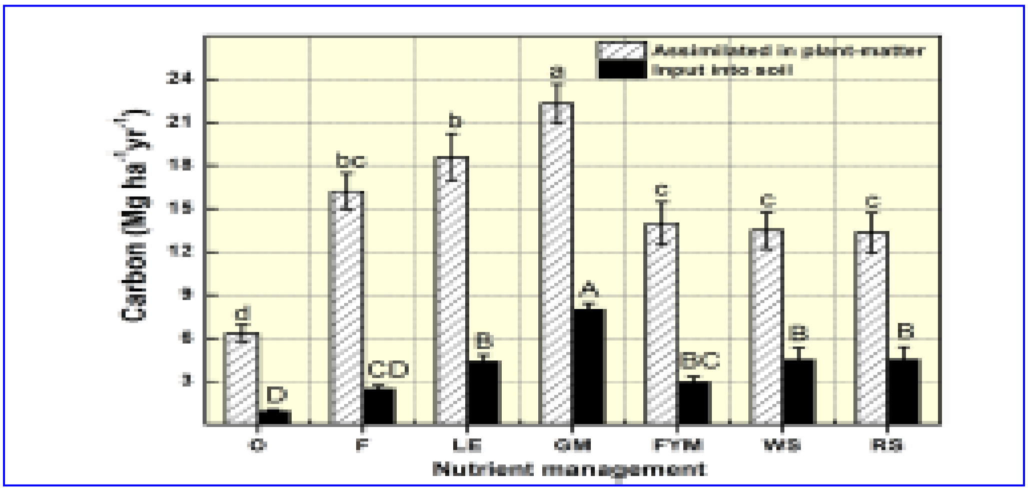




**Figure 13: Carbon (C) assimilated in the nutrient management systems and C input (*ex situ* + *in situ*) into the soil in rice –wheat cropping system**

O=No fertilizer, F= 100 inorganic fertilizer, LE=Legume crop (*Vigna radiata*), GM=Green manuring, FYM=farm yard manure, WS=Wheat stubble, RS=Rice stubble

IIWBR, Karnal, Haryana Ajay *et al.* (2019)

**Conclusion:**

Soil carbon pool plays a crucial role in the soil quality, availability of plant nutrients, environmental functions and global carbon cycle. Agricultural soils are among the earth's largest terrestrial reservoirs of carbon and hold potential for expanded carbon sequestration. Management practices *viz.,* organic agriculture, conservation tillage, mulching, cover crops, INM and agro-forestry, including improved management of pastures and rangelands will aid to sequester carbon. Soil carbon sequestration is yet another strategy towards mitigation of climate change. They provide a prospective way for reducing atmospheric concentration of $CO_2$.

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# DOLICHOS LABLAB (*LABLAB PURPUREUS*) IN TANZANIA: A CLIMATE-RESILIENT CROP FOR NUTRITION, SOIL HEALTH, AND LIVELIHOODS

**Pavithravani B Venkataramana**

School of Life Sciences and Bioengineering,

The Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania

*Corresponding author E-mail: pavithravani.venkataramana@nm-aist.ac.tz

**Abstract:**

Dolichos lablab (*Lablab purpureus*) is a versatile legume traditionally cultivated in Africa and Asia, increasingly recognized for its potential in sustainable agriculture, food and nutrition security, and climate resilience. In Tanzania, recent research and seed release efforts have revived the role of Dolichos lablab as both a food and fodder crop. This chapter integrates published research on Tanzanian lablab farming systems and drought evaluation, highlighting its genetic diversity, farm-level utilization, and adaptive potential under climate stress. Case studies and empirical results from field research are used to demonstrate the crop's contribution to smallholder livelihoods, soil fertility, and resilience. The discussion emphasizes its role in advancing food security, supporting integrated farming systems, and positioning Dolichos lablab as a strategic crop for future food systems in sub-Saharan Africa.

**Keywords:** Dolichos Lablab, Tanzania, Genetic Diversity, Drought Tolerance, Climate Resilience, Legumes, Sustainable Agriculture, Food Security

**1. Introduction:**

Legumes play a pivotal role in African farming systems. They contribute significantly to food and nutrition security by providing affordable plant-based proteins, essential minerals, and vitamins, while simultaneously enhancing soil health through biological nitrogen fixation (Giller, 2001). Among the wide range of legumes, Dolichos lablab (*Lablab purpureus* L.) occupies a unique position as a multipurpose crop. Known by various local names, including Ngwara / Fiwi in Tanzania, lablab is cultivated as a food grain, a leafy vegetable, livestock fodder, and a cover crop that supports soil conservation (Maass *et al.,* 2010). Its versatility has made it an important crop in smallholder farming systems, especially in areas facing unpredictable rainfall and harsh conditions.

Although lablab is native to Africa, it has been widely disseminated and adapted across Asia, America, and Australia due to its diverse uses and resilience (Pengelly & Maass, 2001). In East Africa, however, its cultivation remains limited when compared to other legumes such as common beans (*Phaseolus vulgaris*) or cowpea (*Vigna unguiculata*). This underutilization is paradoxical given lablab's ecological adaptability and its ability to thrive under marginal conditions where other crops often fail (Haque *et al.,* 2020). In Tanzania, recent research highlights its promise as a crop that strengthens food security, restores soil fertility, improves nutrition, and supports livelihoods in both semi-arid and sub-humid zones (Mcharo *et al.,* 2023). Traditionally, lablab has been cultivated in intercropping systems with cereals such as maize, sorghum, and millet. Importantly, lablab was regarded as a *famine-reserve food*, particularly valued during periods of drought when other food sources were scarce (Msuya *et al.,* 2017). Its young leaves and pods continue to be consumed as leafy vegetables in many rural communities, thereby diversifying diets and addressing micronutrient deficiencies.

In the current era of climate change, lablab is gaining renewed scientific and policy attention as a climate-smart crop. It tolerates drought, has deep rooting systems, and contributes to soil organic matter improvement, making it a valuable crop for climate adaptation and mitigation (Whitbread *et al.,* 2011). Furthermore, research and development initiatives in Tanzania are focusing on seed system improvement, participatory varietal selection, and integration into sustainable farming systems (Mcharo *et al.,* 2023). Farmer-led innovations, supported by research institutions, are helping reposition lablab as a strategic crop that enhances resilience in farming systems.

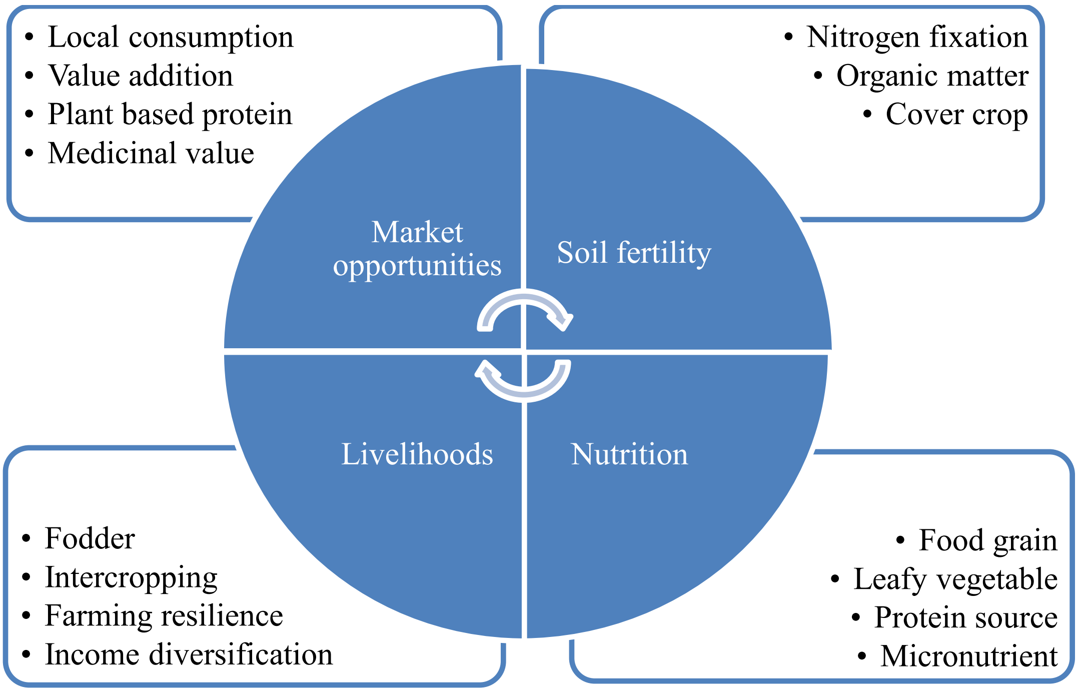


**Figure 1: The multifunctional role of lablab contributing to food security and resilience**

This chapter synthesizes recent Tanzanian studies and experiences to highlight the emerging role of lablab in addressing interconnected challenges of nutrition, soil health, and livelihoods. By examining its historical relevance, current uses, global trade, economic opportunities and future prospects, the discussion underscores the importance of mainstreaming lablab into agricultural development strategies for a resilient and sustainable food system in Tanzania.

**2. Nutritional Significance**

From a nutritional perspective, Dolichos lablab is a highly valuable food source. Its dry beans contain 20–28% protein, alongside essential minerals such as calcium (60–80 mg per 100 g) and iron (5–7 mg per 100 g), as well as substantial dietary fiber (8–12%) (Rai *et al.,* 2018). The young leaves and pods are also consumed as vegetables, providing additional micronutrients and contributing to food security. These properties are particularly relevant in regions where protein-energy malnutrition is prevalent, offering an affordable and locally available source of high-quality nutrition. Furthermore, lablab's nutrient composition compares favorably with other commonly consumed legumes, including common beans, cowpea, and soybean, demonstrating its potential as a dietary staple in diverse communities (Table 1).

**Table 1: Nutritional composition of Dolichos lablab compared with other legumes (per 100 g dry matter).**

| Crop | Protein (%) | Calcium (mg) | Iron (mg) | Dietary Fiber (%) |
|---|---|---|---|---|
| Dolichos lablab | 20–28 | 60–80 | 5–7 | 8–12 |
| Common bean | 18–22 | 40–60 | 4–6 | 7–10 |
| Cowpea | 22–25 | 45–65 | 5–8 | 6–9 |
| Soybean | 35–40 | 200 | 9–11 | 5–7 |

Source, Authors computation 2025

In addition to human nutrition, Dolichos lablab plays a critical role in livestock systems. Its foliage serves as high-quality forage, with crude protein levels ranging from 15–24%, which has been shown to enhance milk production, growth rates, and overall animal health (Tuin *et al.,* 2019). The dual-purpose nature of lablab providing both human food and livestock feed makes it an integral part of mixed farming systems. By integrating lablab into cropping-livestock interactions, farmers can reduce dependence on external feed sources, lower production costs, and improve farm resilience against climatic and economic shocks. The crop's ability to sustain livestock during dry periods further strengthens food security at the household level, highlighting its multifunctional value in tropical and subtropical agricultural landscapes.

Dolichos lablab also offers important ecosystem benefits. Its nitrogen-fixing capacity reduces the need for chemical fertilizers, lowering greenhouse gas emissions and enhancing soil microbial activity. When intercropped with cereals or other legumes, it can improve soil structure, suppress weeds, and increase overall farm biodiversity. These attributes align with climate-smart agricultural principles, promoting sustainability while simultaneously enhancing nutrition and livelihoods.

**3. Global Trade and Economic Opportunities**

Beyond its local significance, lablab presents emerging opportunities in regional and global markets. In India, for example, it is consumed as a staple pulse, widely integrated into diets as split dal, flour, or vegetable pods (Haque *et al.,* 2020). In Australia and Brazil, lablab has gained popularity as a high-quality forage crop for livestock industries due to its protein-rich biomass and adaptability to tropical and subtropical climates (Whitbread *et al.,* 2011). Such international demand illustrates the potential for Tanzania and other African countries to position lablab as an export-oriented legume, particularly given its African origin and the growing global shift toward plant-based proteins. With increasing consumer awareness of the nutritional and ecological benefits of underutilized legumes, lablab could be marketed as a niche, climate-resilient crop in specialty and health food markets.

Economically, lablab holds strong potential for livelihood diversification and income generation among Tanzanian smallholders. Strengthening value chains from seed production, processing, and packaging to market access could transform lablab from a subsistence crop into a commercial enterprise. Development of farmer cooperatives, community seed banks, and linkages with agribusiness actors can enhance its profitability. Additionally, investment in processing technologies, such as dehulling, fortification, and product development (snacks, flours, plant-based meat alternatives), could expand consumer demand and add value locally (Mcharo *et al.,* 2023). By tapping into both domestic and international markets, lablab can provide new economic opportunities while contributing to food system transformation and resilience in Tanzania.

**4. Dolichos Lablab in Tanzania: Research and Advances**

Tanzania has emerged as a regional leader in Dolichos lablab research. The Nelson Mandela African Institution of Science and Technology, in collaboration with national partners, has released two improved varieties tailored for drought-prone areas. These varieties outperform local landraces in terms of yield potential, disease resistance, and adaptability to varying agroecological conditions.

Seed system strengthening is ongoing, involving farmer cooperatives and seed enterprises to ensure wider distribution of improved lablab seeds. This transition is critical because historically, lablab seed has been maintained informally by farmers, limiting genetic gain and productivity improvements. At the policy level, there is increasing recognition of the importance of underutilized crops like lablab in contributing to the objectives of food security, nutrition improvement, and climate adaptation. Some of the research highlights are presented.

**4.1 Lablab Farming Systems in Tanzania**

The study on *Lablab purpureus* in Tanzania provides an in-depth analysis of its cultivation, distribution, farming systems, and climatic trends across five agro-ecological zones

(Julius *et al.,* 2023). Surveys and participatory research revealed that Lablab is cultivated in 17 districts, 80 wards, and 98 villages, with notable genetic diversity reflected in over 50 landraces distinguished by seed color and local names. Despite being an underutilized crop, Lablab remains vital for multiple purposes: conservation agriculture and soil fertility (27.9%), marketing (22.1%), livestock feeding (21.5%), food during drought (15.4%), and traditional uses (7.4%).

Farming systems are dominated by intercropping (59%) and monocropping (31%), with minor practices such as home gardening, crop rotation, and relay cropping. Farmers primarily select landraces based on seed parameters (color, size, shape), which also influence market and consumption preferences. Black seeds dominate in northern zones due to demand from Kenyan markets, while white and cream seeds are preferred locally for food. Key challenges identified include low yields, unavailability of improved varieties, pest and disease pressures, high input costs, poor market channels, and inadequate storage facilities. Despite these constraints, Lablab is recognized as a drought-resilient crop grown mainly in arid and semi-arid zones, with significant potential for enhancing food security, nutrition, soil health, and livelihoods.

**4.2 Breeding for Drought Tolerance and Climate-Smart Accessions**

Multi-environment trials in Tanzania evaluated 12 lablab accessions under stress-free and terminal moisture stress conditions (Missanga *et al.,* 2023). Sites included Arumeru, Same, and Selian, representing diverse rainfall and temperature regimes. Accessions such as D147, D363, HA4, D349, D352, D348, and D359 demonstrated superior drought tolerance and yield potential. Drought tolerance indices including mean productivity, geometric mean productivity, and stress tolerance index confirmed their suitability for semi-arid zones. These findings validate lablab's capacity to thrive at rainfall as low as 200 mm and temperatures up to 35°C, highlighting its strategic role in climate adaptation.

**4.3 Farmers' Participatory Plant Selection**

Modern breeding techniques often exclude farmers' input, leading to low adoption rates of improved varieties. Participatory breeding fosters collaboration between researchers and farmers, enhancing crop variety adoption. Letting *et al.* (2022) emphasized the importance of integrating indigenous knowledge with scientific research for effective breeding programs. The study focused on the participatory breeding approach for lablab in Tanzania, highlighting farmers' preferences and production constraints. Participatory evaluation was conducted with 31 farmers from Arusha, Kondoa, Karatu, Same, and Babati districts and data was collected through semi-structured questionnaires and focus group discussions. Major constraints identified include pests and diseases (83.9%), poor marketability (38.7%), and inadequate rainfall. Farmers preferred traits for improvement includes disease resistance, early maturity, high yield, and specific seed color preferences. EK2, D360, HA4, and D96 were the genotypes identified to be preferred by farmers.

Kissa *et al.* (2019) focused on the participatory approach to improving lablab bean cultivation in northern Tanzania. The study highlighted the nutritional and environmental benefits of lablab beans, their declining cultivation due to factors like unavailability of improved varieties, low yields, and pest issues, and the importance of farmer involvement in breeding. Through field trials and surveys, farmers identified key traits such as high yield, early maturity, disease resistance, and drought tolerance are to be considered for future breeding. The study underscores the value of participatory research in enhancing adoption, utilization, and genetic diversity of lablab beans, ultimately contributing to food security and sustainable agriculture.

**4.4 Indigenous Lablab Rhizobia of Tanzania**

Rhizobia are gram-negative soil bacteria that form symbiotic relationships with legumes, fixing atmospheric nitrogen for plant use. The study by Eliah *et al.* (2020) aimed to isolate and characterize indigenous rhizobia from Lablab purpureus in Babati district, Tanzania, to enhance understanding of their symbiotic potential. The study identified significant diversity among rhizobia, which is crucial for developing effective biofertilizers tailored to local conditions. Isolates were categorized as slow (27%) or fast (73%) growers, with most colonies being circular and exhibiting convex elevation. All isolates demonstrated motility, with variations in mucus production noted, which is important for stress adaptation and nodulation.

All isolates tested positive for catalase activity, indicating the presence of the enzyme that protects against oxidative stress. The isolates showed varying growth responses to different carbon sources, with mannitol being the most effective. Growth was significantly reduced in acidic conditions (pH 4.5), while most isolates thrived in alkaline conditions (pH 8.5 and 9.5). Salt tolerance was assessed, revealing that most isolates could grow in 1% NaCl, but growth declined sharply at higher concentrations (3% and 4% NaCl). Temperature tolerance varied, with optimal growth at 30°C; some isolates managed to grow at 45°C, indicating potential for adaptation to warmer climates. The ability of certain isolates to tolerate stress conditions such as acidity, salinity, and high temperatures suggests their potential for enhancing nitrogen fixation in challenging environments. Further research is recommended on specific isolates (e.g., BR3, BR18, BR20) to explore their genetic characteristics and symbiotic efficiency, which could improve legume production in Tanzania and similar regions.

**Conclusion:**

Overall, Dolichos lablab represents a climate-resilient, nutrient-rich, and multi-functional legume with immense potential to support sustainable farming systems in Tanzania and across Africa. Its integration into mixed farming systems not only addresses human nutritional needs but also strengthens livestock productivity, soil health, and farm resilience. Promoting its wider cultivation and consumption can contribute to more diversified, sustainable, and climate-adapted agricultural landscapes.

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# THRIPS DIVERSITY IN HIMACHAL PRADESH: THEIR IDENTIFICATION AND MANAGEMENT

**Aditi Aggarwal[1] and Sangita Sharma*[2]**

[1]Dr. Yashwant Singh Parmar University of Horticulture and Forestry,
Department of Entomology, Nauni, Solan-173230(HP), India

[2]Dr. Y.S. Parmar University of Horticulture and Forestry,
Regional Horticultural Research & Training Station, Mashobra, Shimla-171007(HP), India

*Corresponding author E-mail: sangitasharmaento@gmail.com

**Abstract:**

Thrips (Order: Thysanoptera) are among the most important insect pests of agriculture and horticulture. They cause both direct damage by feeding and indirect damage as vectors of plant viruses. In Himachal Pradesh, a region with diverse agro-climatic conditions, thrips infest a wide variety of crops, including vegetables, fruits, ornamentals, and medicinal plants. This chapter provides an extensive account of thrips biology, diversity, symptoms of damage, virus transmission, monitoring, and integrated pest management strategies. Special attention is given to crop-wise thrips diversity in Himachal Pradesh, supplemented with case studies from the region. The chapter concludes with an emphasis on sustainable management and future prospects for integrating modern tools such as molecular identification and precision agriculture.

**Keywords:** Thrips, Diversity, Sampling, Virus Transmission, Integrated Pest Management, Sustainable, Agriculture

**Introduction:**

Members of the insect order Thysanoptera with two recognized suborders, the Terebrantia and Tubulifera, are commonly called thrips. These are tiny insects, usually less than 2 mm long, and not readily noticeable, which includes more than 6,000 described species worldwide (Lewis, 1973). Typically, the adults have four slender wings, each with a long fringe of marginal cilia, but the most remarkable feature of thrips is the asymmetry of their mouthparts, that is only the left mandible is present. About 50% of them are fungal feeders, while 40% feed on living tissues of plants, and some are predatory (Morse and Hoddle, 2006). Some species also act as vectors of plant viral diseases (Ghosh *et al*., 2017). They are characterized by their fringed wings, asymmetrical piercing-sucking mouthparts, and remarkable ecological adaptability. These features allow them to occupy diverse habitats and feed on a wide range of plant species, making them important agricultural pests. Globally, thrips infest cereals, vegetables, fruits, ornamentals, and plantation crops. They are responsible for billions of dollars in economic losses due to their ability to cause both direct feeding damage and indirect viral transmission (Nagata *et al*., 2004).

Feeding by thrips results in silvering, curling, flower abortion, and scarring on fruits, while their role as vectors of tospoviruses makes them especially damaging.

India provides highly suitable conditions for thrips diversity due to its varied agro-climatic zones. In Himachal Pradesh, thrips infest major crops like apple, plum, apricot, walnut, onion, garlic, capsicum, chilli, rose, chrysanthemum, and gladiolus (Sanjta & Chauhan, 2015; Sanjta *et al*., 2018). The economic importance of horticulture in this state makes thrips management a top priority for farmers and researchers. Thrips are also notorious for their ability to develop resistance to insecticides. Their short life cycle, overlapping generations, and cryptic habits allow them to escape control measures and quickly adapt to new conditions (Riley *et al*., 2014). Thus, a detailed understanding of thrips biology, diversity, and integrated management is critical for sustainable agriculture in Himachal Pradesh.

**Biology and Ecology of Thrips:**

Thrips undergo an intermediate type of metamorphosis with distinct egg, larval, prepupal, pupal, and adult stages. Females insert their eggs into plant tissues, where they remain protected. The larvae resemble adults in structure but lack wings and are voracious feeders. The prepupal and pupal stages are non-feeding and usually occur in the soil or concealed plant parts, providing a survival advantage. Adults emerge with fringed wings and are capable of dispersal, aided by wind currents. The entire life cycle may be completed in 15–30 days depending on temperature and host plant availability, allowing multiple overlapping generations per season. This rapid reproduction enhances their potential as pests and facilitates the development of insecticide resistance.

Thrips exhibit diverse feeding behaviors, ranging from pollen feeding to leaf and flower feeding. Some species are highly host-specific, while others are polyphagous. Their feeding results in the rupture of plant epidermal cells and the sucking of cellular contents, leading to visible damage on host plants.

**Diversity of Thrips in Himachal Pradesh:**

Himachal Pradesh has four main agroclimatic zones: the Sub-Tropical Zone (Zone I), the Mid Hills Zone (Zone II)), the High Hills Temperate Zone (Zone III) and the Cold Dry Zone (Zone IV). These zones are defined by differences in altitude, temperature, rainfall, and soil type, which influence the types of crops cultivated. Himachal Pradesh, with its varied topography and climatic conditions, harbors a rich thrips fauna. Members of the families Thripidae, Aeolothripidae, and Phlaeothripidae are recorded, with Thripidae being the most dominant. Extensive surveys conducted in vegetables, fruits, and ornamentals have revealed the presence of multiple thrips species across different districts (Sanjta & Chauhan, 2015; Sanjta *et al*., 2018; Singh *et al*., 2020). In vegetables, *Thrips tabaci* is widespread on onion, garlic, and capsicum, while *Scirtothrips dorsalis* is common on chilli and capsicum. *Thrips palmi* occurs on cucurbits and onion, whereas Aeolothrips indicus has been recorded from carrot crops.

In fruits, *Aeolothrips collaris* has been found on apple in Kinnaur, while *Thrips carthami* occurs on apple and plum in Shimla. In high density apple plantation in Shimla district greater abundance of blossom thrips, *Thrips flavus* Schrank was recorded by Kumari *et al*. (2022). Walnut, apricot, and plum are infested by *Thrips palmi*, and grapevines are attacked by *Rhipiphorothrips cruentatus*. Ornamental crops such as iris, carnation, gladiolus, rose, and chrysanthemum is also heavily infested by thrips. Species like *Frankliniella schultzei*, *Thrips simplex*, *Megalurothrips distalis*, and *Haplothrips clarisetis* are of economic importance. These infestations cause serious damage in commercial floriculture, which is a growing sector in Himachal Pradesh. The thrips fauna associated with different vegetables, fruits, ornamentals and medicinal plants is documented in Table 1 as under:

**Table 1: Thrips fauna of Himachal Pradesh**

| Sr. No. | Thrips species | Agro-climatic zone | Place | Host/Habitat |
|---|---|---|---|---|
| **Suborder: Terebrantia** | | | | |
| **Family: Aeolothripidae** | | | | |
| 1. | *Aeolothrips collaris* Priesner | II, III, IV | Kinnaur, Solan, Nauni | Apple, Arrow leaf Dock, Calendula |
| 2. | *Aeolothrips distinctus Bhatti* | II | Nauni, Palampur | Nasturtium, Parthenocarpic Cucumber |
| 3. | *Aeolothrips indicus* Bhatti | II | Nauni | Calendula, Lupin, Carrot |
| 4. | *Aeolothrips intermedius Bagnall* | II | Nauni | Chrysanthemum |
| 5. | *Aeolothrips nigricornis* Ananthakrishnan | II | Nauni | Brinjal, wallflower |
| **Family: Thripidae** | | | | |
| **Sub Family: Panchaetothripinae** | | | | |
| 1. | *Helionothrips aino* (Ishida) | II | Mandi | Colocasia |
| 2. | *Retithrips syriacus* Mayet | II | Nauni | Achania |
| 3. | *Rhipiphorothrips cruentatus* Hood | I, II, III, IV | All over the state | Grape vine |
| **Sub Family: Sericothripinae** | | | | |
| 1. | *Hydatothrips proximus* Bhatti | II | Dharampur | Deodar, Pinus |

| | | | | |
|---|---|---|---|---|
| 2. | *Neohydatothrips samayankur* Kudo | I, II | Nauni, Nurpur, Palampur | Asparagus, Cauliflower, Marigold |
| **Sub Family: Thripinae** | | | | |
| 1. | *Anaphothrips obscures* (Muller) | - | - | - |
| 2. | *Anaphothrips sudanensis* Trybom | I, II | Govindsagar, Nauni | Carrot, Chilli, Patchouli |
| 3. | Aptinothrips rufus (Haliday) | - | - | - |
| 4. | *Ayyaria chaetophora* Karny | II | Nauni, Solan | Cucumber, Soybean |
| 5. | *Bathrips melanicornis* (Shumsher) | I, II | Chamba, Kangra, Mandi | Arundo (Spanish cane), Mustard, Amaltas, Patchouli |
| 6. | *Caprithrips melanophthalmus* (Bagnall) | - | - | Grass |
| 7. | *Ctenothrips barapatharensis* Tyagi, Ghosh and Kumar | II | Dalhousie (Bara Pathar) | Ferns |
| 8. | *Ctenothrips niger* Kudo | II | Dalhousie | Unidentified plant |
| 9. | *Ctenothrips smilax* Bhatti | III | Narkanda | Ferns and herbage |
| 10. | *Dendrothripoides innoxius* Karny | II | Mandi | General vegetation |
| 11. | *Ernothrips lobatus* (Bhatti) | - | - | - |
| 12. | *Florithrips traegardhi* (Trybom) (syn. *Taeniothrips fulvus* Ananthakrishnan and Jagadish) | II | Kasauli, Kullu, Solan | Barley, Rose, Strawberry |
| 13. | *Frankliniella schultzei* (Trybom) (syn. *Frankliniella sulphurea* Trybom) | II | Nauni, Solan | Iris, Wild Himalayan Cherry, Carnation |
| 14. | *Lefroyothrips lefroyi* (Bagnall) | I, II | Bajaura, Dharmshala, Kangra Valley, Nauni, Solan | Chinese cabbage, Chinese mustard, Rose, Tea |
| 15. | *Megalurothrips distalis* (Karny) | II | Katrain, Manali, Nauni | Dahlia, Rose, Sweet pea |
| 16. | *Megalurothrips peculiaris* Bagnall | II | Nauni, Rajgarh, Solan | Bean, Calendula, Cauliflower, Cucumber |

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|---|---|---|---|---|
| 17. | *Megalurothrips usitatus* (Bagnall) | II | Solan | Lentil, Peach |
| 18. | *Microcephalothrips abdominalis* (D.L. Crawford) | II | Bajaura, Katrain, Mandi, Solan | Arundo (Spanish cane), Chrysanthemum, Dahlia, Lupin, Marigold, Solidago, Zinnia |
| 19. | *Moundinothrips robustus* (Bhatti) | III | Shimla | Fern |
| 20. | *Mycterothrips nilgiriensis* (Ananthakrishnan) | - | - | - |
| 21. | *Mycterothrips ricini* (Shumsher) | - | - | - |
| 22. | *Oxythrips indicus* Bhatti | II | Kasauli | - |
| 23. | *Oxythrips kochummani* Ananthakrishnan | III | Shimla | Deodar |
| 24. | *Parabaliothrips takahashii* Priesner | III | Shimla | Mixed Vegetation |
| 25. | *Scirtothrips dorsalis* Hood | I, II, III | Bilaspur, Chamba, Govindsagar, Kangra, Mandi, Nauni, Rajgarh | Capsicum, Carrot, Chandrashur, Chilli, Euphorbia, Mimosa, Castor, Weeping willow |
| 26. | *Scirtothrips kenyensis* Mound | II | Mandi | Tea |
| 27. | *Scirtothrips mangiferae* Priesner | II | Mandi | Unidentified plant |
| 28. | *Scolothrips rhagebianus* Priesner | II | Palampur | Parthenocarpic cucumber |
| 29. | *Scolothrips sexmaculatus* (Pergande) | II | Nauni | Rose, Strawberry |
| 30. | *Smilothrips productus* Bhatti | II | McLeodganj | Grass |
| 31. | *Stenchaetothrips biformis* (Bagnall) | I, II | Kangra Valley | Rice |
| 32. | *Stenchaetothrips bambusae* (Shumsher) | I | Bilaspur, Gobindsagar, Hamirpur | Ageratum, Bamboo, Bamboo leaves |

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|---|---|---|---|---|
| 33. | *Stenchaetothrips pteratus* Bhatti | III | Kufri | Grass |
| 34. | *Taeniothrips bharokariiensis* Kumar and Tyagi | III | Bharokari | Fern |
| 35. | *Taeniothrips major* Bagnall | - | - | - |
| 36. | *Tameothrips arundo* Tyagi and Kumar | II | Mandi | Arundo (Spanish cane) |
| 37. | *Thripsalatus* Bhatti | I, II | Bilaspur, Nauni | Ageratum, Fenugreek |
| 38. | *Thrips andrewsi* (Bagnall) | II | Nauni, Palampur | Rose, Lantana, Lupin |
| 39. | *Thrips apicatus* Priesner | I, II | Kangra | Hedge with violet flowers |
| 40. | *Thrips arorai* Bhatti | III | Shimla | Ferns |
| 41. | *Thrips carthami* Shumsher | II, III | Kasauli, Kinnaur, Nauni, Shimla | Apple, Berberis, Calendula, Fenugreek, Lupin, Marigold, Nasturtium, Pansy, Patchouli, Plum, Radish, Sweet alyssum |
| 42. | *Thrips cedri* Bhatti | III | Dhalli | Deodar |
| 43. | *Thrips coloratus* Schmutz | II | Dharmshala, Palampur | Grass, Tea |
| 44. | *Thrips dorax* Bhatti | II | Kasauli | Salvia |
| 45. | *Thrips flavidulus* (Bagnall) | II | Dharampur, Kasauli, Khaltu, Nauni | Achania, Berberis, Cauliflower, Fenugreek, Kale, Marigold, Pansy |
| 46. | *Thrips flavus* Schrank (syn. *Taeniothrips rhopalntennalis* Shumsher) | II, III, IV | Chamba, Dharampur, Gaura, Kasauli, Khaltu, Kinnaur, Kullu, Nauni, Pandah, Rajgarh, Shimla, Solan | Apple, Apricot, Bean, Beet, Bitter gourd, Broccoli, Calandula, Capsicum, Carnation, Chinese cabbage, Coriander, Cornflour, Fenugreek, Flax, Gaillardia, Garlic, Geranium, Grapes, Hyacinth, Kale, Kainth, |

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|---|---|---|---|---|
| | | | | Marigold, Mustard, Narcissus, Nasturtium, Okra, Onion, Pea, Peach, Pear, Pecan, Phlox, Plum, Pomegranate, Poppy, Prinsepia, Radish, Rumex, Rose, Stock, Sweet pea |
| 47. | *Thrips florum* Schmutz | I, II, III | Chamba, Gaura, Kangra, Mandi, Nauni, Nurpur | Arabian, Jasmine, Amaltas, Arundo (Spanish Cane), Cactus flowers, Dahlia, Euphorbia, Pumpkin, Rose, Tea flowers, White flowers, White rose |
| 48. | *Thrips formosanus* Priesner | II | Nauni | Paja, Plum |
| 49. | *Thrip shawaiiensis* (Morgan) | I, II, III | Chamba, Dhaulakuan, Gaura, Nauni, Kasauli, Kullu, Naggar, Palampur, Solan | Achania, Apple, Dahlia, Carnation, Chinese cabbage, Citrus, Cucurbits, Gladiolus, Rose of Sharon, Marigold, Prinsepia, Rose, Turnip, Wheat |
| 50. | *Thrip shimalyanus* Pelikan | II | Nauni | African Daisy, Kale, Marigold, Sweet alyssum |
| 51. | *Thrips kodaikanalensis* Ananthakrishnan and Jagadish | II | Kullu, Nauni | Flax, Helichrysum, Hyacinth, Mustard, Radish, Stock |
| 52. | *Thrips longiceps* (Bagnall) | II | Nauni | Brinjal |
| 53. | *Thrips meridionalis* Priesner | II | Nauni | Coriander |
| 54. | *Thrips moundi* Tyagi and Kumar | III | Shimla | Grass |

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|---|---|---|---|---|
| 55. | *Thrips palmi* Karny | I, II | Bilaspur, Gaura, Govindsagar, Kangra, Khaltu, Nangil, Nauni, Palampur, Rajgarh, Solan | Ageratum, Apricot, Brinjal, Calendula, Cluster fig (Goolar), Coriander, Creeping herb with bluish violet flowers, Cucumber, Eucalyptus, Lupin, Marigold, Mustard, Mixed herb, Nasturtium, Onion, Pansy, Parthenium, Parthenocarpic cucumber, Pea, Pecan nut, Plum, Radish, Sweet alyssum, Walnut |
| 56. | *Thrips setosus* Moulton | II | Nauni | Calendula, Lupin, Sweet William |
| 57. | *Thrips simplex* (Morison) | II | Nauni | Gladiolus |
| 58. | *Thrips subnudula* (Karny) | II | Mandi, Solan | Acacia, Solidago |
| 59. | *Thrips tabaci* Lindeman | I, II | Bajaura, Banjar, Barthin, Chamba, Gaura, Jogindernagar, Kangra, Khaltu, Kullu, Nadaun, Nagarota, Bagwan, Nauni, Nurpur, Palampur, Pandah, Rajgarh, Sarkaghat, Solan, Sundernagar, Una | Apricot, Bean, Beet, Bougainvillea, Brinjal, Broccoli, Calendula, Capsicum, Chrysanthemum, Coriander, Fenugreek, Garlic, Helichrysum, Hyacinth, Hydrangea, Lentil, Onion, Pea, Peach, Pear, Plum, Radish, Tomato, Walnut |
| 60. | *Thrips xenos* Bhatti | II | McLeodganj | Grass |

| | | | | |
|---|---|---|---|---|
| **Suborder: Tubulifera** | | | | |
| **Family: Phlaeothripidae** | | | | |
| **Sub Family: Idolothiripinae** | | | | |
| 1. | *Ethirothrips vitreipennis* (Priesner) | - | - | - |
| 2. | *Opthalomothrips breviceps* (Bagnall) | III | Shimla | - |
| **Sub Family: Phaleothipinae** | | | | |
| 1. | *Haplothrips (Haplothrips) bagrolis* Bhatti | I | Bagrol | Wheat |
| 2. | *Haplothrips (Haplothrips) magniferae* Priesner | - | - | - |
| 3. | *Haplothrips (Haplothrips) ceylonicos* Schmutz | II | Solan | Pecan nut |
| 4. | *Haplothrips (Trybomiella) clarisetis* Priesner | II | Nauni | Chrysanthemum, Helichrysum |
| 5. | *Haplothrips (Haplothrips) ganglhaueri* Schmutz | II | Palampur, Solan | Lentil, Prinsepia, Rice, Rubus |
| 6. | *Haplothrips (Haplothrips) gowdeyi* (Franklin) | II | Kullu, Solan | Gaillardia, Poplar, Wax gourd |
| 7. | *Haplothrips (Trybomiella) nigricornis* (Bagnall) | II | Kasauli, Solan | Carnation, Chilli, Poplar, Rose of Sharon |
| 8. | *Haplothrips tenuipennis* Bagnall | I, II, III, IV | Gaura, Kangra, Kinnaur, Nauni, Ochhghat, Palampur, Rajgarh, Shimla, Solan | Apple, Apricot, Berberis, Brinjal, Chrysanthemum, Cucumber, Dahlia, Helichrysum, Pansy, Peach, Pear, Pecan nut, Pomegranate, Pumpkin, Rice, Rose, Sweet William, Tea, Tomato, Walnut |
| 9. | *Liothrips (Liothrips) renukae* Muraleedharan and Sen | I | Renuka | Leaf gall of unknown plant |

(Source: Sanjta *et al*., 2018; Singh *et al*., 2020)

**Identification of Thrips:**

The erroneous identification of an economically important species may have parallel and serious ramifications as it will generate confusing data for other fields of biology. The precise identification of thrips species is the first and fundamental step to develop genetic and other biological information that is essential for effective management strategies. The identification of thrips species is primarily based on morphological characters such as color, chaetotaxy, body architecture, etc. However, their minute size, cryptic behavior, sexual dimorphism, high degree of similarity in various developmental stages and polymorphism (in color, wing development, body size, etc.) are some of the obstacles for morphology based identification. Considering these difficulties, it is vital to use supporting methods to identify thrips species and resolve other taxonomic issues. Molecular tools have been found useful in the last decade to supplement various fields of biology ranging from systematics to ecology.DNA Barcoding employs the partial fragments of mitochondrial cytochrome *c* oxidase I gene (mt COI) for species-level identification, and this has gained wide acceptance as a supplementary method to resolve taxonomic ambiguities (Tyagi *et al*., 2017). Mitochondrial genes have also been used to estimate genetic diversity below species level. Its utility as a rapid and authentic tool for species identification is well recognized in a wide variety of animal taxa across the globe. This technique has also been used in thrips identification1 detection of cryptic species, invasive genetics, population structure, development of species-specific markers and phylogenetic analysis.

**Symptoms of Damage:**

Thrips feeding causes distinctive symptoms on leaves, flowers, and fruits. Leaves develop silvering, stippling, curling, and distorted growth due to epidermal cell damage (Bethke, 2014). In chilli and capsicum, feeding causes leaf curling and fruit deformation, reducing both yield and quality. Flowers show discoloration, malformation, and premature drop, which significantly reduces fruit set in crops like chilli, onion, and capsicum. In ornamentals such as chrysanthemum and rose, even minor infestations reduce the aesthetic and market value of flowers (Sanjta *et al*., 2018). Both nymphs and adults feed on floral parts and delicate leaves of vegetativebuds by sucking the sap therefore, causing reduction in fruit set and yield. Apale area, known as "pansy spot," develops around the scar where eggs weredeposited, and is especially noticeable on light-skin apple cultivars. reduce consumer acceptance (Sharma *et al*. 2023). In grapes, damage by *Rhipiphorothrips cruentatus* reduces berry size and market quality.

In fruit trees both nymphs and adults cause serious damage to growing tissue of plant such as leaves, flowers, fruits and young shoots by sucking the sap therefore, causing reduction in fruit set and yield. In extreme cases leaves and flowers become dry and fall off prematurely. The attacked flowers show withering symptoms, as a result either fruits do not set or many fall off in early stages of development. Some of thrips produce galls by rolling, folding or wrinkling the leaves and few galls develop on flowers. A pale area, known as "pansy spot", develops around the scar where eggs were deposited, and is especially noticeable on light-skin apple cultivars. The attacked leaves and flowers may fall off prematurely. Some of the thrips produce galls by rolling, folding or wrinkling the leaves and few galls develop on flowers. Heavily infested flowers produce distorted blossoms which may open on one side. The damage is perceptible from somewhat dull unsightly and sticky colour of blossom. Infestation results in poor setting and excessive fruit drop. The fruit setting in infested orchards, is sometimes reduced to 50% as compared to plants free from thrips attack (Sharma and Chauhan, 2024).

**Thrips as Vectors of Plant Viruses:**

Thrips are one of the major sucking pests, that can seriously hamper crop production by direct feeding damage and acting as vectors of Tospoviruses (genus Tospovirus, family Bunyaviridae). These are RNA viruses transmitted by thrips and are one of the most important plant viruses. Thrips are the sole transmitters of Tospoviruses, affecting plant species in several unrelated plant families across the globe. Their ability to act as vectors for these viruses has severely hampered the agricultural economy over the past two decades.

The peculiarity in tospovirus transmission by thrips is that only larvae can acquire the viruses while adults can transmit. Currently, 15 species in six genera (*Ceratothripoides, Dictyothrips, Frankliniella, Neohydatothrips, Scirtothrips* and *Thrips*) of subfamily Thripinae (Thripidae) have been reported as vectors for tospoviruses (Whitefield *et al.,* 2005 and Riley *et al.,* 2011). Thrips acquire the virus during the larval stage and transmit it throughout their adult life (Nagata *et al.,* 2004). More than 20 tospoviruses are transmitted exclusively by thrips, making them one of the most economically important insect vectors.

In India, Tomato Spotted Wilt Virus (TSWV), Groundnut Bud Necrosis Virus (GBNV), and Watermelon Silver Mottle Virus are important thrips-transmitted viruses. In Himachal Pradesh, *Thrips tabaci* and *Thrips palmi* are reported vectors of TSWV and GBNV, causing severe damage to vegetable and ornamental crops.

**Sampling and Monitoring of Thrips:**

Accurate monitoring of thrips populations is essential for effective management. Absolute sampling methods include direct collection from plants, leaf beating, and Berlese funnel extraction. Relative methods such as sweep nets, suction traps, and sticky traps are widely used for field surveys (Marullo *et al*., 2021). Yellow and blue sticky traps are particularly effective for monitoring thrips in greenhouse and open-field conditions. Reflective mulches are used not only as a monitoring tool but also for repelling thrips from crops. Recent technological advances include AI-based sticky traps, drone surveillance, and IoT-enabled pest monitoring systems (Riley *et al*., 2014).

**Integrated Pest Management (IPM) of Thrips:**

Thrips are the major threat for the crops and various species of thrips has been reported to developresistance to different group of insecticides (Kalyan *et al*., 2012).Insecticideresistance has continued to be a widespread problem with the thrips, as populations have continued to evolve resistance to all manner of new insecticides (Gao *et al*., 2012).Therefore, to combat insecticide resistance in the thrips an integrated approach is required for effective and sustainable thrips management. The following strategies have been successfully employed:

**1. Cultural and mechanical control:**

Crop rotation, removal of alternate host plants, and timely sowing reduce thrips infestations. Digging the basins of the tree with spades during winter (December-January) to expose the diapausing pupae to adverse climatic conditions. Intercropping with non-host species and the use of reflective mulches, employing sprinkler irrigation to disrupt thrips activity and pruning infested shoots provide additional protection (Kumar *et al*., 2020).

**2. Physical Control:**

Installing blue or yellow sticky traps for monitoring and mass trapping, UV-reflective films, and insect-proof nets are effective in reducing thrips populations. Soil solarization in nurseries helps reduce the pupal population.

**3. Biological Control:**

Various species havebeen reported to feed on thrips. The most abundant group of natural enemies of thrips are eulophids, anthocorid bugs, predatory mites, coccinellids, neuropterans, cecidomyiid and spiders (Yee *et al*., 2000). Predatory bugs (*Orius* spp.), lacewings (*Chrysoperla* spp.), predatory mites (*Euseius* spp.), and spiders naturally regulate thrips populations. Aeolothrips intermedius, a predatory thrips species, has shown promise in reducing onion thrips populations (Abenaim *et al*., 2022).

**4. Chemical Control:**

Insecticides are used during severe infestations, though resistance development is a major challenge. Newer molecules like spinetoram, tolfenpyrad, and broflanilide have proven effective (Muralimohan *et al*., 2023). Apply thiacloprid 21.7 per cent SC at initiation of pink bud stage, if the number of thrips is more than 5/flower. Rotation of insecticides with different modes of action is recommended.

**5. Eco-Friendly Approaches:**

Neem-based formulations and entomopathogenic fungi such as *Beauveria bassiana* are promising eco-friendly alternatives. These options reduce dependence on chemical pesticides and are safer for pollinators and natural enemies.

**Case Studies:**

Sanjta and Chauhan (2015) surveyed vegetables in Himachal Pradesh and documented 13 thrips species across multiple districts. Sanjta *et al*. (2018) expanded this work in ornamentals, reporting 26 species and highlighting their economic importance.

Singh *et al.* (2020) recorded 65 species belonging to 29 genera of Thripidae, confirming the rich thrips diversity in Himachal Pradesh. Abenaim *et al*. (2022) demonstrated the effectiveness of *Aeolothrips intermedius* as a predator, showing 88.9% predation on onion thrips. Muralimohan *et al*. (2023) evaluated insecticides against *Thrips parvispinus* on chilli, with broflanilide providing superior control.

**Future Prospects:**

The future of thrips management in Himachal Pradesh lies in integrating modern tools with traditional practices. Molecular techniques such as DNA barcoding and next-generation sequencing will aid in accurate species identification. Climate change studies are necessary to predict thrips outbreaks under changing environmental conditions. Precision agriculture tools, including sensor-based monitoring and AI-driven forecasting, will revolutionize thrips management. The development of resistant crop varieties and the use of botanicals and microbial pesticides will form the backbone of eco-friendly management in the coming decades.

**Conclusion:**

Thrips are among the most important pests of horticultural crops in Himachal Pradesh. They cause significant losses through direct feeding and virus transmission. Management strategies must focus on integrated approaches combining cultural, physical, biological, chemical, and eco-friendly methods. Case studies from Himachal Pradesh highlight the diversity and economic significance of thrips, as well as the effectiveness of integrated pest management. Future research should focus on molecular tools, resistant varieties, and precision farming technologies for sustainable thrips management.

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## About Editors

Dr. Archana Suyal holds a M.Sc. and Ph.D. in Agricultural/Analytical Chemistry from G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand. She was awarded the prestigious DST-Inspire fellowship and her doctoral thesis work was recognized as the Best Thesis by the North American Chemical Residue Workshop (NACRW). Dr. Suyal is currently serving as Scientist (R&D) at Patanjali Natural Coloroma, Patanjali Group. With over a decade of research experience in the analytical field, she has worked as SRF and RA in various reputed organizations. She has authored many publications in national and international journals and has actively presented her research at several scientific conferences. In 2024, she received the Distinguished Research Excellence Award at an international conference. She is also a life member of multiple professional scientific bodies, reflecting her commitment to research and the scientific community.

Mr. C. P. Bhagat is an accomplished academician in the Department of Botany at Karmaveer Hire College, Gargoti, Dist. Kolhapur, Maharashtra. With 12 years of teaching experience and four years of research experience, he has significantly contributed to botanical education and research. He has published 10 research articles and authored four book chapters, reflecting his scholarly engagement in the field. Additionally, he has served as an editor for two books, showcasing his expertise and commitment to academic publishing. Mr. Bhagat has also played an active role in organizing conferences and workshops, fostering academic growth and collaborative learning among students and faculty. His dedication to teaching, research, and knowledge dissemination continues to inspire students and peers in the field of Botany and Life Sciences.

Dr. Dinesh Daujirao Wanule is an Assistant Professor of Zoology at B. K. Birla College (Autonomous), Kalyan, with nearly 20 years of teaching and research experience. He holds an M.Sc. in Zoology (Entomology) and a Ph.D. from SRTM University, Nanded, where he worked on insects as antimicrobial sources, along with a Postgraduate Diploma in Bionanotechnology from the University of Mumbai. His research interests span entomology, animal husbandry, and sustainable development. He has published 26 research papers, secured 11 patents, and contributed multiple book chapters, and he is a recognized PG teacher under the University of Mumbai. Dr. Wanule has received prestigious honors including the UGC's Rajiv Gandhi National Fellowship, the Global Eminent Research Award (2023), and the Best Researcher Award (2025), reflecting his dedication to impactful zoological research.

Mr. Sandeep Kumar is a dedicated educator and researcher in Agricultural Extension with over seven years of teaching experience as an Assistant Professor. He holds a B.Sc. (Hons.) in Agriculture from Swami Keshwanand Rajasthan Agricultural University, Bikaner, an M.Sc. in Agricultural Extension from SHUATS, Prayagraj, and a Ph.D. from Sri Karan Narendra Agriculture University, Jobner. Passionate about guiding students and advancing agricultural knowledge, he has developed academic content, published research papers and articles in reputed journals and magazines, and actively participated in various national and international trainings, seminars, and conferences. A proud member of professional bodies including the Society for Extension Education Gujarat (SEEG) and the Indian Society of Extension Education (ISEE), ICAR–New Delhi, he strongly believes in using education as a tool to empower rural communities and bridge research with real-world farming practices.

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