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INTEGRATED APPROACHES IN AGRICULTURE ENGINEERING



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Bhumi Publishing, India



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Integrated Approaches in Agriculture Engineering

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PREFACE

Agriculture remains the backbone of human progress, sustaining livelihoods and driving economic development across the world. In the present era, however, this vital sector faces multiple challenges including climate variability, soil degradation, water scarcity, and the urgent demand for sustainable food production. To meet these challenges, there is a growing need to integrate innovative scientific research with practical engineering solutions that ensure both productivity and sustainability.

*The book *Integrated Approaches in Agriculture Engineering* is an effort to present such advancements, combining diverse areas of knowledge to strengthen agricultural practices. This volume explores a wide spectrum of themes such as farm mechanization, irrigation management, soil and water conservation, post-harvest technology, renewable energy in agriculture, and precision farming. Each contribution emphasizes the importance of linking traditional wisdom with modern technology, thereby offering holistic solutions for sustainable agricultural development.*

Prepared by experienced academicians and researchers, the chapters bring together theoretical insights and practical applications. They highlight emerging techniques, case studies, and field-level interventions that can be readily adapted by farmers, professionals, and policymakers. By focusing on integration and innovation, this book underscores the critical role of agricultural engineering in addressing current challenges and shaping the future of agriculture.

We believe this volume will serve as a valuable reference for students, researchers, teachers, professionals, and entrepreneurs in the agricultural sciences and allied disciplines. It will also benefit extension workers and decision-makers who are engaged in formulating strategies for sustainable agricultural growth.

As editors, we sincerely thank all the contributors for their scholarly work, dedication, and timely cooperation. We also acknowledge the support of the publishing team in bringing this book to fruition. It is our hope that this volume will provide meaningful insights, stimulate further research, and contribute to the advancement of integrated approaches in agriculture engineering.

- Editors

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BIOCHAR FOR SUSTAINABLE SOIL MANAGEMENT: MECHANISMS, APPLICATIONS AND FUTURE PERSPECTIVES

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Abstract:

Biochar, a carbon-rich material produced through the pyrolysis of diverse organic biomass, has attracted considerable interest as a multifunctional amendment for sustainable soil management. Its unique physicochemical properties—such as high porosity, large surface area, alkaline pH and chemical stability—contribute to improvements in soil structure, nutrient cycling and water-holding capacity. These characteristics not only enhance soil fertility and crop productivity but also play a critical role in long-term carbon sequestration, thereby supporting climate change mitigation strategies. This chapter discusses the mechanisms underlying biochar–soil interactions, including its influence on microbial activity, nutrient availability and heavy metal immobilization. Biochar’s ability to adsorb and retain essential nutrients reduces leaching losses, increases nutrient-use efficiency and promotes root growth, while simultaneously remediating contaminated soils and mitigating greenhouse gas emissions. The integration of biochar with organic manures, chemical fertilizers and beneficial microbial inoculants is increasingly recognized as a promising approach to maximize agronomic and environmental benefits. Despite these advantages, several challenges hinder the widespread adoption of biochar. High production and transportation costs, variability in quality depending on feedstock and pyrolysis conditions and limited farmer awareness remain critical constraints. Addressing these issues requires the development of cost-effective production technologies, standardized guidelines for biochar application and supportive government policies to encourage adoption, particularly among smallholder farmers. Looking ahead, biochar holds strong potential as a cornerstone of climate-smart agriculture. Its use, when strategically integrated into soil fertility management practices, can contribute to sustainable crop production, soil health restoration and environmental resilience in the face of global challenges such as soil degradation, food insecurity and climate variability.

Introduction:

Sustainable soil management is increasingly recognized as a cornerstone in addressing the interconnected global challenges of food security, environmental degradation and climate change. Rapid population growth and rising food demand have intensified agricultural production, often at the expense of soil quality. Conventional practices, particularly the excessive reliance on chemical fertilizers, have resulted in nutrient imbalances, soil acidification, organic matter depletion and the decline of beneficial microbial communities (Lal, 2015; Ahemad and Kibret, 2014). These trends threaten the long-term productivity and resilience of agricultural systems, highlighting the urgent need for sustainable alternatives. In this context, biochar has emerged as a promising amendment to restore and maintain soil health while enhancing agricultural productivity. Biochar is a carbon-rich material produced through the pyrolysis of organic biomass under limited oxygen conditions (Lehmann and Joseph, 2015). Unlike traditional organic amendments, its highly stable carbon structure, large surface area and porous nature confer unique properties that improve soil fertility, water retention and nutrient use efficiency (Schmidt *et al.*, 2021). Moreover, biochar has the capacity to sequester carbon in soils over centuries, thereby contributing to climate change mitigation (Woelf *et al.*, 2010). The interest in biochar is not new; its role in enhancing soil fertility can be traced back to the ancient “Terra Preta” soils of the Amazon Basin, which remain highly fertile to this day due to their biochar content (Glaser *et al.*, 2001). Modern scientific research has revived this knowledge, positioning biochar as a multifunctional tool not only for crop productivity but also for environmental remediation, waste management and greenhouse gas reduction (Biederman and Harpole, 2013; Agegnehu *et al.*, 2017).

This chapter provides a comprehensive overview of biochar as a sustainable soil management strategy. It examines the mechanisms through which biochar interacts with soil systems, including nutrient dynamics, microbial activity and soil structure modification. Furthermore, it explores practical applications in agriculture, environmental benefits and current limitations hindering large-scale adoption. Finally, the chapter discusses future perspectives, with emphasis on biochar’s integration into climate-smart agricultural practices, policy frameworks and innovative biochar-based technologies for global soil sustainability. The concept of amending soil with charred organic matter is not new. Ancient Amazonian civilizations created remarkably fertile, dark soils known as *Terra Preta de Índio* (Amazonian Dark Earths) by incorporating charcoal, bone and other organic

wastes into the naturally poor soils of the region. These soils have maintained their high fertility for centuries, showcasing the long-term potential of carbon-rich amendments. Modern science has revisited this ancient practice through the lens of biochar, defined as the solid, carbonaceous product obtained when biomass is subjected to thermal decomposition under low-oxygen or anoxic conditions. Biochar can be produced from a wide variety of organic feedstocks, including agricultural residues (e.g., straw, husks), forestry waste (e.g., wood chips, bark) and animal manures. The production process can be tailored—primarily through controlling the pyrolysis temperature and heating rate—to yield biochars with distinct properties. Slow pyrolysis typically maximizes the biochar yield, producing a highly stable material, whereas fast pyrolysis yields more liquid (bio-oil) and gaseous (syngas) co-products that can be used for energy generation. This versatility positions biochar production within a circular bioeconomy framework, transforming waste streams into valuable products for soil enhancement and energy.

Definition

Biochar is a stable, carbon-rich and porous material produced by the thermal decomposition of organic biomass under limited or no oxygen conditions, a process known as pyrolysis. Common feedstocks for biochar include agricultural residues, animal manures, forestry wastes and municipal organic wastes. Unlike conventional organic amendments such as compost or manure, biochar is characterized by its long-term stability, large surface area and high porosity, which enable it to persist in soils for decades to centuries. These properties make biochar an effective soil amendment for enhancing fertility, retaining water and nutrients, supporting microbial communities and sequestering carbon (Lehmann and Joseph, 2015).

Importance of Biochar in Soil

Biochar has emerged as a multifunctional soil amendment that plays a vital role in improving soil health, agricultural productivity and environmental sustainability. Its unique physical and chemical properties make it distinct from traditional organic inputs such as compost or manure. The importance of biochar in soil can be explained under the following points:

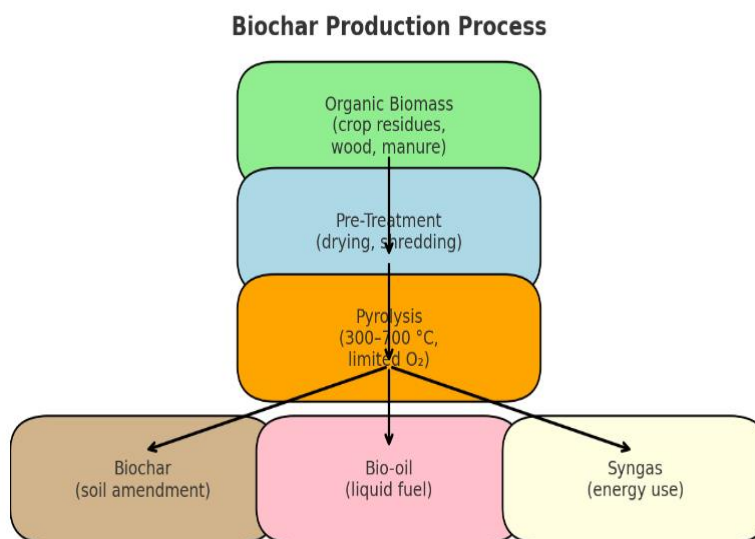
I. Improvement of Soil Fertility

Biochar provides a porous structure and high surface area that enhances nutrient retention and reduces leaching losses. It acts as a slow-release nutrient reservoir, holding essential elements like nitrogen, phosphorus, potassium and

trace minerals. When combined with compost or fertilizers, biochar increases nutrient-use efficiency.

II. Enhancement of Soil Physical Properties

In sandy soils, biochar increases water retention and reduces drought stress. In clay soils, it improves aggregation and aeration, reducing compaction. Its lightweight, porous structure enhances root penetration and overall soil tilth.



III. Promotion of Soil Biological Activity

Biochar serves as a habitat for beneficial soil microorganisms, including nitrogen-fixing bacteria and mycorrhizal fungi. It promotes microbial diversity and enzymatic activities that are essential for nutrient cycling. This leads to improved plant-microbe interactions and healthier rhizosphere conditions.

IV. Carbon Sequestration and Climate Benefits

Biochar is a highly stable form of carbon that can remain in soils for hundreds to thousands of years. Its application contributes to climate change mitigation by reducing atmospheric CO₂ levels. It reduces greenhouse gas emissions (N₂O and CH₄) from soils by altering microbial processes.

V. Reduction of Soil Acidity and Contaminants

Biochar often has an alkaline pH, which helps neutralize acidic soils and improves nutrient availability. It adsorbs and immobilizes toxic elements (e.g., heavy metals, pesticides), reducing their bioavailability to plants. Acts as a natural filter, improving soil quality in polluted or degraded lands.

VI. Contribution to Sustainable Agriculture

Enhances crop yield and resilience under stress conditions (drought, salinity). Reduces dependence on chemical fertilizers, lowering farming costs and environmental risks. Supports organic and eco-friendly farming systems.

Biochar Production Process

Biochar is produced through pyrolysis, the thermal decomposition of organic biomass under limited or no oxygen conditions. This process is central to determining the physical, chemical and biological properties of biochar, such as pH, nutrient content, porosity, surface area and stability (Lehmann and Joseph, 2015). Hence, understanding the production process is critical to designing biochar with desired qualities for agricultural and environmental applications.

The first step is biomass selection, where a wide range of feedstocks can be utilized, including agricultural residues (e.g., rice husk, maize stalks, sugarcane bagasse), forestry wastes (e.g., wood chips, bark) and animal manures. The chemical composition of the feedstock, especially its carbon, nitrogen, lignin and ash content, strongly influences the nutrient profile and stability of the biochar produced (Manya, 2012). Hence, the choice of feedstock determines the final performance of biochar in soil.

Following selection, pre-treatment is often required to ensure efficiency in the pyrolysis process. Typically, biomass is air-dried to reduce its moisture content to below 20% and size reduction (through chopping or shredding) is carried out to allow for uniform heating during carbonization (Downie *et al.*, 2009). Hence, pre-treatment minimizes energy losses and ensures a consistent biochar product.

The central stage is pyrolysis, carried out in reactors with controlled temperature and oxygen supply. Slow pyrolysis (300–500 °C) maximizes biochar yield, producing highly stable carbon suitable for soil amendment and long-term carbon sequestration (Lehmann *et al.*, 2006). Fast pyrolysis (500–700 °C) produces less biochar but more bio-oil and syngas, which are valuable for renewable energy (Demirbas, 2004). At even higher temperatures, gasification (>800 °C) mainly generates syngas, with biochar as a minor byproduct. Hence, the pyrolysis temperature and heating rate largely dictate the proportion and quality of products obtained.

The process yields three major by-products. Biochar is the carbon-rich, porous solid used for soil amendment, carbon sequestration and pollution remediation. Bio-oil is a liquid fuel with potential for bioenergy and chemical extraction, while syngas (CO, H₂, CH₄) can be used to generate electricity and heat (Bridgwater, 2012). These co-products highlight the versatility of pyrolysis systems in contributing to a circular bioeconomy.

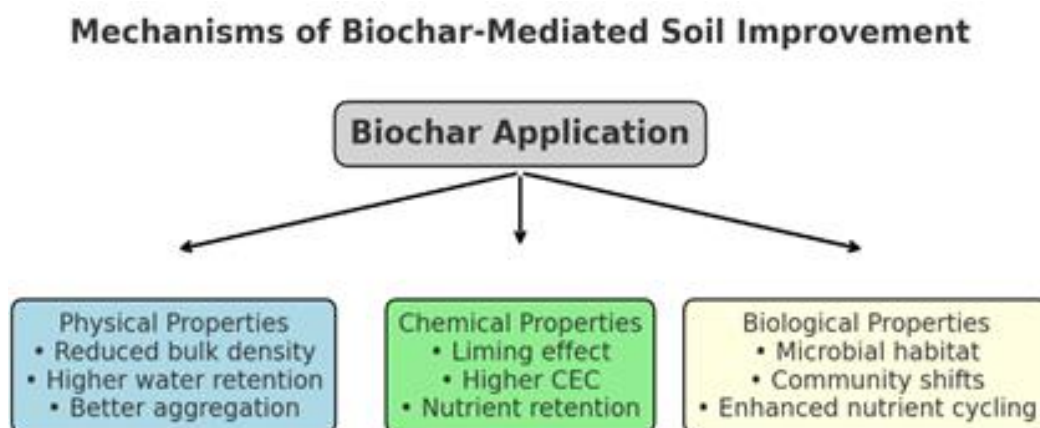
Finally, post-processing involves cooling and collecting biochar, followed in some cases by enrichment or activation with nutrients or minerals to create “designer biochars”

with targeted agronomic or remediation benefits (Schimmelpfennig and Glaser, 2012). Hence, the overall production process—from feedstock selection to post-treatment—not only influences carbon stabilization efficiency but also determines the environmental and agricultural performance of biochar.

Mechanisms of Biochar-Mediated Soil Improvement

The addition of biochar to soil brings about significant improvements in its physical, chemical and biological properties. From a physical perspective, biochar is considerably lighter than mineral soil particles and its incorporation reduce the overall bulk density of soil. This makes the soil more friable and porous, which in turn facilitates better root penetration and aeration. Moreover, the highly porous structure of biochar acts much like a sponge, increasing the soil's water-holding capacity and making crops more resilient to drought stress, particularly in sandy soils (Glaser *et al.*, 2002). Biochar also contributes to soil aggregation by binding particles together into stable aggregates, thereby enhancing infiltration, aeration and resistance to erosion.

In terms of chemical properties, biochar often has an alkaline nature, which can neutralize soil acidity. This liming effect reduces aluminum (Al^{3+}) toxicity and improves nutrient availability for plants. Additionally, biochar possesses a high cation exchange capacity (CEC) due to its functional surface groups, allowing it to retain essential nutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+). This nutrient-retentive quality reduces leaching losses and enhances fertilizer efficiency. The porous structure of biochar also serves as a reservoir, slowly releasing adsorbed nutrients over time, which supports sustained soil fertility.



Biologically, biochar creates favorable conditions for microbial life by offering protective microhabitats within its pores. These microenvironments reduce microbial

exposure to predators and moisture stress, allowing populations to thrive (Quilliam *et al.*, 2013). The presence of biochar in soil often leads to shifts in microbial community composition, encouraging beneficial organisms such as nitrogen-fixing bacteria and mycorrhizal fungi. Through these interactions, biochar indirectly enhances nutrient cycling by stimulating microbial processes like nitrogen mineralization, thereby contributing to improved soil fertility and ecosystem functioning.

Applications in Sustainable Agriculture and Environmental Management

The application of biochar in agriculture and environmental systems has gained global recognition due to its multi-functional role in improving crop productivity, mitigating climate change and remediating polluted soils. Its unique physical and chemical characteristics make it a sustainable solution to pressing agricultural and environmental challenges.

i. Enhancing Crop Productivity

Biochar enhances soil fertility by improving nutrient retention, cation exchange capacity and water-holding ability. These changes create a more favorable environment for root growth and microbial activity, thereby supporting higher crop yields. Meta-analysis by Jeffery *et al.* (2011) demonstrated significant yield benefits, particularly in acidic and degraded soils, where biochar's liming effect and nutrient retention capacity are most effective. Hence, biochar not only boosts crop productivity but also reduces dependence on synthetic fertilizers.

ii. Carbon Sequestration and Climate Change Mitigation

Biochar plays a critical role in climate change mitigation by locking atmospheric carbon into stable, aromatic structures that persist in soils for centuries to millennia. This long-term storage makes biochar a "carbon-negative" technology. Additionally, it reduces emissions of potent greenhouse gases such as nitrous oxide (N₂O) and methane (CH₄) by improving soil aeration and influencing microbial processes. Hence, biochar application not only sequesters carbon but also minimizes agricultural greenhouse gas emissions, contributing to global climate goals.

iii. Environmental Remediation

Beyond agriculture, biochar serves as an effective tool for environmental remediation due to its high surface area and strong adsorption capacity. It immobilizes toxic heavy metals such as lead (Pb), cadmium (Cd) and arsenic (As) through surface complexation and precipitation, thereby reducing their bioavailability to plants and

organisms. Similarly, it adsorbs organic pollutants like pesticides and hydrocarbons, preventing their leaching and accumulation in the food chain. Hence, biochar offers a sustainable approach to restoring soil quality in contaminated environments.

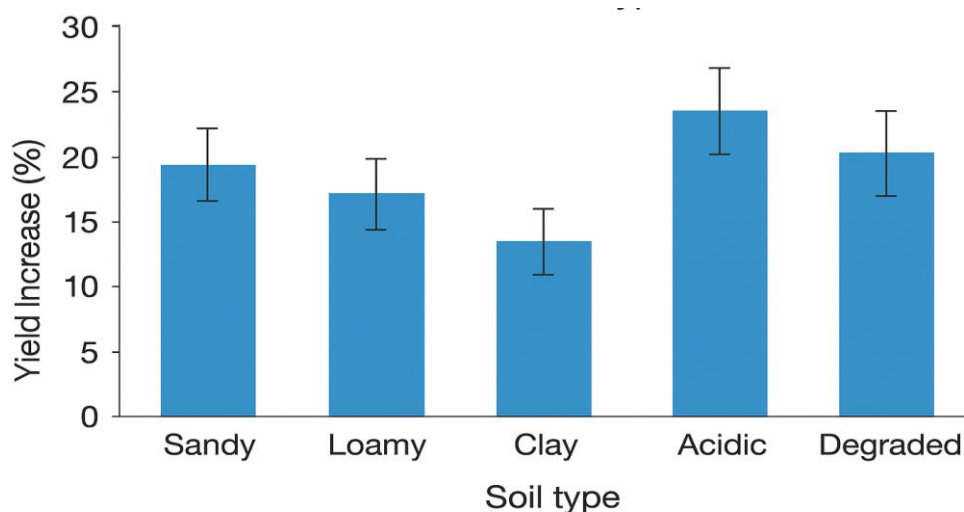


Figure 1: Crop yield increases under biochar application across soil types

Properties of Biochars from Different Feedstocks

Biochars produced from different biomass feedstocks exhibit distinct physicochemical characteristics, which largely determine their agricultural and environmental applications. Rice husk biochar generally shows an alkaline pH (8.2), high cation exchange capacity (CEC, 85 cmol/kg) and a considerable surface area (120 m²/g). Its high silica (Si) content makes it effective for improving soil fertility and serving as a pH amendment in acidic soils. Poultry manure-derived biochar, with a strongly alkaline pH (9.1), high CEC (95 cmol/kg) and nutrient-rich profile dominated by nitrogen (N) and phosphorus (P), is particularly suited for direct nutrient enrichment in cropping systems. In contrast, biochar produced from wood chips tends to have a neutral to slightly alkaline pH (7.5), moderate CEC (70 cmol/kg) and very high surface area (250 m²/g). Despite its relatively low nutrient content, its porous structure makes it valuable for enhancing soil physical properties and long-term carbon sequestration. Sugarcane bagasse biochar typically has a pH of 8.0, a CEC of 75 cmol/kg and a moderate surface area of 150 m²/g. With a balanced nutrient profile, particularly moderate potassium (K) levels, it is effective in promoting crop yield enhancement. Hence, the feedstock selection directly influences the functional role of biochar, from soil fertility improvement to climate change mitigation, proving its versatile potential in sustainable soil management.

Table 1: Typical Properties of Biochars Produced from Different Feedstocks

Feedstock	pH	CEC (cmol/kg)	Surface Area (m ² /g)	Nutrient Content	Application Potential
Rice husk	8.2	85	120	High Si	Soil fertility, pH amendment
Poultry manure	9.1	95	80	High N, P	Nutrient enrichment
Wood chips	7.5	70	250	Low nutrients	Soil structure, carbon sequestration
Sugarcane bagasse	8.0	75	150	Moderate K	Crop yield enhancement

Physicochemical Properties

Biochar exhibits a wide range of physicochemical characteristics that determine its interaction with soils and plants. Its high porosity and large surface area improve soil aeration and water-holding capacity, while also providing microsites for microbial colonization. The alkaline pH of most biochars helps neutralize soil acidity, improving nutrient availability in acid soils. Its cation exchange capacity (CEC) and surface functional groups (–OH, –COOH) enhance the adsorption and retention of essential nutrients such as ammonium, phosphate and potassium, thereby reducing leaching losses. The carbon structure of biochar is chemically stable, contributing to long-term carbon sequestration and persistence in soils for decades to centuries. However, the properties of biochar vary considerably depending on feedstock type (crop residues, manure, wood) and pyrolysis conditions (temperature, residence time). For example, high-temperature biochars typically show greater surface area and stability, whereas low-temperature biochars retain more labile carbon and nutrients. Such variability necessitates careful selection and standardization for field applications.

Benefits of Biochar

Environmental Impacts

Biochar plays a dual role in improving soil health and addressing environmental challenges. Its stable carbon structure contributes to long-term carbon sequestration, directly mitigating climate change by capturing atmospheric CO₂ in solid form. Moreover, biochar can reduce greenhouse gas (GHG) emissions from soils, particularly nitrous oxide (N₂O) and methane (CH₄), by improving soil aeration and influencing microbial processes

such as denitrification. In addition, biochar is widely recognized for its potential in soil remediation. It immobilizes heavy metals like cadmium, lead and arsenic, reducing their bioavailability and toxicity to plants. Its high surface area also enables adsorption of organic pollutants such as pesticides and polycyclic aromatic hydrocarbons (PAHs). By lowering contaminant mobility, biochar protects groundwater and enhances soil resilience. When integrated into waste management systems, biochar production further contributes to a circular economy, transforming agricultural residues into a value-added product.

Soil Fertility and Productivity

The application of biochar offers significant agronomic advantages. It improves soil fertility by retaining nutrients and reducing leaching losses, thereby increasing nutrient-use efficiency and lowering the need for chemical fertilizers. Biochar also improves soil structure and aggregation, which enhances root penetration, reduces compaction and promotes soil aeration. Its high water-holding capacity supports crops under drought stress, making it particularly useful in semi-arid and rainfed regions. Biochar also stimulates soil microbial activity by providing habitat niches within its porous structure. This leads to increased populations of beneficial microbes, including plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi. Consequently, biochar application often translates into higher crop productivity and improved plant health. When combined with organic manures, chemical fertilizers, or microbial inoculants, biochar acts synergistically, enhancing nutrient availability and crop yield more effectively than when used alone. For smallholder farmers, biochar represents a pathway toward sustainable and climate-smart agriculture—improving yields, restoring degraded soils and reducing environmental risks while contributing to long-term soil health.

Case Studies in Indian Context

India has witnessed several field and pot trials demonstrating the benefits of biochar under varied agro-climatic conditions, including in the states of Rajasthan and Uttarakhand, both of which offer distinct challenges and opportunities due to their soil types, climatic stress (e.g. water scarcity, steep terrain) and high availability of biomass residues.

In Uttarakhand, research at G. B. Pant University of Agriculture and Technology (Pantnagar) has shown promising results. In direct-seeded rice (DSR) systems, enriched biochar-based fertilizers enhanced growth, yield and nutrient-use efficiency, while also improving soil chemical and biological properties. For instance, application of enriched

biochar improved activities of soil enzymes (dehydrogenase, urease, alkaline phosphatase) during flowering in rice, indicating improved soil biological health. Another Uttarakhand study with poultry-litter biochar applied with reduced fertilizer levels improved both growth and economics in baby corn under pot conditions. Also, for sweet corn, the combination of enriched biochar + organic manures led to greater plant height and dry matter compared to controls. In another trial, biochar-coated nitrogen (slow-release forms) in wheat in the Indo-Gangetic Plains (Pantnagar) helped retain biomass, tiller number and height, compared to neem-coated urea under different N-doses.

In Rajasthan, several trials address both water stress and fertility management. A notable field experiment at Udaipur (Rajasthan College of Agriculture, MPUAT) during the rabi season 2021-22 assessed wheat under various levels of water stress and biochar. Biochar at 3 and 4 t/ha increased grain yield by about 12-13% compared to no biochar under water stress, demonstrating its potential to buffer against drought effects. Another study in Rajasthan looked at “Effect of Fertility Levels and Biochar on Soil Health and Productivity of Wheat”. In that study, wheat variety Raj-4037 was grown with different rates of fertilizers (75-125% RDF) and biochar (0, 4, 8, 12 t ha⁻¹). The results showed that higher biochar rates along with recommended or slightly higher fertilizer doses improved soil health and productivity over control. A physiological-biochemical study showed that in wheat under water stress, biochar at 4 t/ha improved relative water content (RWC), though effects on chlorophyll and proline were mixed.

These case studies illustrate that even in semi-arid, resource-limited regions like parts of Rajasthan and in the hilly, variable-rainfall terrains of Uttarakhand, biochar can contribute positively to crop yield, soil health and resilience to stress when applied at moderate rates (often 2-5 t/ha up to ~10-12 t/ha, depending on crop, soil and water availability). It's also clear that combining biochar with enriched fertilizers or organic inputs tends to give synergistic gains in performance.

Role of Biochar in Indian Soils

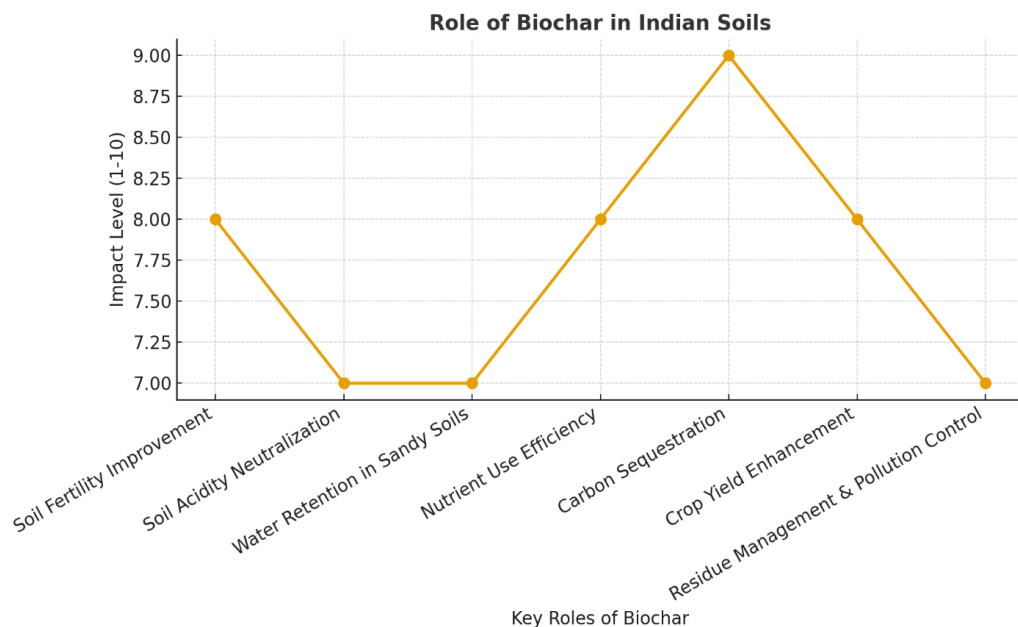
India's agricultural soils face multiple and complex challenges, including nutrient depletion, loss of organic matter, soil acidity, salinity and the increasing vulnerability of farming systems to climate change. Biochar, produced through the pyrolysis of organic residues under limited oxygen supply, offers a sustainable and multifunctional strategy to tackle these challenges by improving soil health, enhancing nutrient-use efficiency and promoting long-term carbon sequestration. In the acidic soils of eastern and northeastern

India, biochar application has shown promise due to its alkaline nature, which helps neutralize soil acidity, thereby improving the availability of essential nutrients such as phosphorus, calcium and magnesium while reducing aluminum and manganese toxicity. This has direct implications for crop productivity in regions where acid soils constrain agricultural growth. Similarly, in sandy soils of Rajasthan and other arid and semi-arid regions, biochar improves soil aggregation and water-holding capacity, mitigating the effects of prolonged droughts and irregular rainfall patterns. By increasing soil porosity and reducing bulk density, biochar supports deeper root penetration and better soil moisture retention, which are crucial for sustaining crops under water-limited conditions. In the Indo-Gangetic plains, one of India's most intensively cultivated regions, continuous high-input farming practices have led to soil nutrient imbalance, organic matter depletion and declining soil fertility.

Biochar application in these soils enhances cation exchange capacity (CEC), improves the retention of nitrogen and phosphorus and reduces nutrient leaching losses, thereby increasing fertilizer-use efficiency. Moreover, biochar's porous structure provides favorable microhabitats for beneficial soil microorganisms, including nitrogen-fixing bacteria and mycorrhizal fungi, which further enhance nutrient cycling and plant growth. Beyond soil fertility management, biochar plays a critical role in climate change mitigation and carbon management. Indian soils, particularly those in tropical and subtropical zones, are typically low in organic matter due to rapid decomposition under high temperatures. The stable aromatic carbon structure of biochar contributes to long-term carbon sequestration, helping reduce greenhouse gas emissions from soils. When combined with crop residues or animal manures, biochar not only stabilizes organic matter but also minimizes methane (CH₄) and nitrous oxide (N₂O) emissions, making it a cornerstone of India's climate-smart agriculture strategies. An additional advantage of biochar in India lies in its ability to utilize locally available agricultural residues as feedstock.

Materials such as rice husk, sugarcane bagasse, cotton stalks, coconut shells and poultry manure can be converted into biochar, providing a low-cost amendment while addressing the environmental problem of open-field residue burning. This dual benefit reduces air pollution, particularly in northern India where stubble burning is a major seasonal issue and at the same time adds value to otherwise underutilized agricultural by-products. Furthermore, biochar has been found effective in remediating degraded and contaminated soils in several Indian contexts. In saline and sodic soils of Gujarat and Uttar

Pradesh, biochar enhances soil structure and facilitates the leaching of excess salts, creating a more favorable environment for crop establishment. In regions facing heavy metal contamination, biochar immobilizes toxic elements such as cadmium, lead and arsenic, thereby reducing their bioavailability and safeguarding food safety. Overall, biochar holds significant potential to strengthen soil resilience, improve crop productivity and contribute to the long-term sustainability of Indian agriculture. However, its successful large-scale adoption will depend on region-specific research trials, the development of cost-effective pyrolysis technologies, policy support for residue management and farmer awareness programs. By integrating biochar into diverse Indian agroecosystems, the country can move closer to achieving sustainable food security, improved environmental health and resilience against climate challenges.



Challenges and Future Perspectives

Despite its potential, biochar application faces several challenges. The economic viability of biochar remains a major constraint, as high production and transportation costs can limit its adoption, particularly among smallholder farmers. Quality standardization is another critical issue, since the properties of biochar can vary widely depending on the type of feedstock and the conditions of pyrolysis. Additionally, significant knowledge gaps exist, with limited region- and crop-specific guidelines to optimize biochar use. Looking ahead, research is increasingly focused on the development of “designer biochars”—engineered forms of biochar specifically tailored to achieve particular goals, such as improving nutrient retention, adsorbing pollutants, or enhancing soil microbial activity.

Addressing these challenges will be essential for realizing the full potential of biochar in sustainable agriculture.

Table 2: Challenges and Future Perspectives of Biochar in Sustainable Soil Management

Category	Challenges / Limitations	Future Perspectives / Solutions
Economic Viability	• High production and transportation costs limit adoption. • Smallholder farmers may struggle to invest without financial incentives or subsidies.	• Promote cost-effective production methods. • Provide subsidies, incentives, or cooperative schemes to support smallholder adoption.
Quality Standardization	• Biochar properties vary depending on feedstock and pyrolysis conditions. • Difficult to ensure consistent performance in soil fertility or other functions.	• Develop standardized production protocols. • Implement quality control measures to ensure uniform properties.
Knowledge Gaps	• Lack of region- and crop-specific guidelines. • Limited information for farmers on optimal dose, timing and application methods.	• Conduct region- and crop-specific research. • Develop extension services and training programs to guide practical applications.
Future Research Directions	• Current research is limited in creating targeted solutions for soil improvement.	• Focus on “designer biochars” tailored for nutrient retention, pollutant adsorption, or stimulation of beneficial microbes. • Study long-term impacts and develop standardized application protocols.

Economic Viability

- The high costs associated with biochar production and transportation limit its widespread adoption.
- Smallholder farmers, in particular, may find it difficult to invest in biochar without financial incentives or subsidies.

Quality Standardization

- Biochar properties can vary significantly depending on the feedstock used and pyrolysis conditions.
- This variability makes it challenging to ensure consistent performance in improving soil fertility or other targeted functions.

Knowledge Gaps

- There is a lack of region- and crop-specific guidelines for optimal biochar application.
- Farmers and practitioners often have limited information on the appropriate dose, timing and method for different soils and crops.

Future Research Directions

- The focus is shifting toward “designer biochars”, engineered to achieve specific objectives.
- These specialized biochars can be tailored for nutrient retention, pollutant adsorption, or stimulation of beneficial soil microbes.
- Developing standardized protocols and understanding long-term effects will help maximize the potential of biochar in sustainable agriculture.

Conclusion:

Biochar presents a promising avenue for sustainable agriculture due to its potential to improve soil fertility, enhance nutrient retention and support long-term soil health. However, several challenges limit its widespread adoption. Economic viability remains a significant barrier, as the production and transportation costs of biochar are high, particularly affecting smallholder farmers who may not have access to financial incentives or subsidies. Quality standardization is another critical issue. The properties of biochar—such as pH, nutrient content and surface area—can vary widely depending on the feedstock and pyrolysis conditions. This variability makes it difficult to ensure consistent outcomes for soil fertility improvement or other agronomic benefits. Moreover, substantial knowledge gaps exist regarding the optimal application of biochar. Region- and crop-

specific guidelines are limited, leaving farmers uncertain about the appropriate doses, timing and methods for applying biochar to achieve maximum benefits. Looking forward, future research is focusing on the development of “designer biochars,” which are engineered to meet specific agricultural objectives, such as enhanced nutrient retention, pollutant adsorption, or stimulation of beneficial soil microbiota. Standardized protocols and comprehensive studies on the long-term effects of biochar are essential to unlock its full potential and facilitate its adoption as a sustainable soil management practice. In summary, while biochar offers significant environmental and agronomic advantages, its practical implementation requires addressing economic constraints, improving quality consistency, bridging knowledge gaps and advancing targeted research to maximize benefits in diverse agricultural systems.

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ANNATTO A NATURAL FOOD COLOURING PLANT: A REVIEW

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Introduction:

Bixa orellana is a quickly-growing shrub that is indigenous to tropical America and is grown there, in the Caribbean, India and most recently, East Africa. Annatto extracts (E160b) are orange/red natural carotenoid colouring agents obtained from the seeds of the tropical shrub *Bixa orellana* Linn and have widespread use in the food industry for the colouring of many commodities (Scotter, 1995). More than 80% of the annatto seed coat's orange-red colour comes from carotenoids and it is made up of *cis*-bixin [methyl hydrogen (9'Z)-6,6'-apocarotene-6,6'-dioate], which, when heated in solution, transforms into a more stable *trans* isomer and a yellow breakdown product (Satyanarayana *et al.*, 2003). Akshatha *et al.* (2011) examined the morphological variation in *Bixa orellana*, which produces the pigment annatto in the aril section of its seeds. Mantovani *et al.* (2013) examined the physical characteristics of fruits from 10 different genotypes cultivated in the Horto of the Federal University of Viçosa, Brazil and evaluated the seed production and bixin content. All examined attributes were considerably different from each other. According to Vilar *et al.* (2014), the annatto seeds contain about 50% carbohydrates, 12 - 17% proteins, 9 - 13% moisture, 5 - 6.8% ash, 2 - 4.8% lipids and 1 - 6.3% lipids. It comprises carotenoids, phenolic compounds, tannins and saponins. Despite having several different names, including "uragumanjal" in Tamil, "japhara" in Telugu, "Iatkan" in Hindi and "Sindhuri" in Sanskrit, it is commonly referred to as the "lipstick tree" throughout India. It is claimed to be grown commercially and is widely distributed throughout India, including Kerala, Karnataka, Tamil Nadu andhra Pradesh, Orissa, West Bengal, Gujarat, Maharashtra, Madhya Pradesh and Chattisgarh. The crop is currently gaining relevance in the food business since the seeds are directly powdered and added to food products in varied amounts because of their beautiful colour shades (Kumaran, 2014).

The five species of *Bixa* are *B. orellana*, *B. urucurana*, *B. arborea*, *B. platycarpa* and *B. excelsa*. The growth habit, which can be either a tree or a shrub, is the fundamental difference between these species (Moreira *et al.*, 2015). The *Bixa orellana* is a wild species

which is grown all over the world because it contains bixin and norbixin. The fruit and the tree are both known by the name “Annatto”. They have several names, such as achiote and urucum. Since it is a tropical plant, annatto may thrive in climates with 280 to 440°C temperatures and 800 to 1500 mm of annual precipitation. Plants have an economic life expectancy of 20 to 25 years.

Dias *et al.* (2017) determined the genotypic variance in the annatto cultivar Embrapa 37 (10 numbers) by studying the physical characteristics of annatto. The genotypes yield dehiscent, simple, bivalve, capsulated and polyspermic fruits. Annatto, also known as achiote, has a fascinating history as a natural colourant. It has been coveted for ages for its vivid red-orange pigment, which has been used to colour a wide range of things, including clothing, cosmetics and food. The Achiote tree is indigenous to tropical areas of South America, which is where annatto first appeared. Indigenous societies in these regions became aware of the vivid red-orange pigment found in the tree's seeds (Iriarte *et al.*, 2020). Annatto was prized for its ability to colour as well as for its culinary and therapeutic use.



(a) Flower of annatto shrub



(b) Fully grown shrub



(c) Freshly matured annatto bunch



(d) Dried annatto bunch

Plate 1: Annatto Variant (TNBI001) at FCandRI, Mettupalayam, TNAU

Umadevi *et al.* (2020) investigated and evaluated the reproductive biology of three annatto cultivars from Tamil Nadu (green fruited), Kerala (red fruited) and Karnataka (dark red fruited). A self- and cross-pollination of the annatto plant was discovered. White pink, light pink and dark pink, respectively, were the floral colours of Tamil Nadu (green-fruited), Kerala (red-fruited) and Karnataka (dark red-fruited). In terms of fruit width (3.48 cm), seeds per fruit (48), 100 seed weight (3.42 g) and yield (111.12 g), Kerala (red fruit) is found to be the best. The fruit was triangular, pyriform and spherical. Bindyalaxmi *et al.* (2022) studied the differences in the bixin and norbixin content, oil content and number of seeds in annatto pods of shape cordate, conical and ovate, along with the colours of annatto pods: maroon pods with maroon spines, green pods with green spines and green pods with green spines.

Economic Importance of Annatto (*Bixa orellana*)

The top three producers and exporters of annatto seeds worldwide are Peru, Brazil and Kenya. In the western hemisphere, other small-scale producers and exporters include the Dominican Republic, Colombia, Ecuador, Jamaica, Costa Rica and Guatemala; in Africa, Cote d'Ivoire and Angola; and in Asia, India, Sri Lanka, Thailand and the Philippines (ITC, (1994)). *B. orellana* is cultivated to some extent for its seeds in the states of Orissa andhra Pradesh and Maharashtra. It has been adopted in the regions of India. McWilliams (2018) predicted that the international carotenoid market was worth \$1.5 billion in 2017 and market surveys for the years 2018 to 2024 predicted that carotenoid market shares varied by industry, including food and beverage (26.1%), pharmaceuticals (9.2%), cosmetics (6.5%), animal feed (34.8%) and dietary supplements (23.5%), respectively.

Mercadante (2000) reported that in terms of economic significance in Latin America, annatto (*Bixa orellana* L.) stands first among naturally occurring pigments. Peru, Brazil and Kenya are the top annatto seed suppliers.

Regulations

The Acceptable Daily Intake (ADI) of 6 to 12 mg bixin/kg body weight and 0.6 mg norbixin/kg body weight was suggested by the Joint Food and Agriculture Organisation (FAO) Expert Committee on Food Additives (JECFA, 67th Meeting 2006.).

ADI of 6 mg bixin/kg body weight (bw) per day and an ADI of 0.3 mg norbixin/kg bw per day. The Regulation (EU) No 231/2012 (Table 1) defines the standards for the food colour E160b (Annatto, Bixin and Norbixin) (Younes *et al.*, 2021).

Principal compound - Bixin

The major colouring component of annatto is the *cis*- bixin ($C_{25}H_{30}O_4$), the monomethyl ester of the dicarboxylic acid *cis*-norbixin (McKeown, 1961). Preston and Rickard (1980) reported that bixin chemistry and stereochemistry have evolved chronologically. The liposoluble di-apo-carotenoid is the main colouring agent in annatto seeds. The monomethyl ester of the water-soluble 9'-*cis*- norbixin is known as 9'-*cis* bixin. Lyng *et al.* (2005) reported that the chain of alternative double-conjugated connections further contributes to the structure of bixin, which confers a few distinctive characteristics. When extracted using an organosolvent and/or heat, this pigment changes from its unstable *cis* to the stable *trans* form. Bixin is a half-ester carotenoid and more precisely a diapo-carotenoid. Historically bixin was the first carotenoid compound in which geometrical isomerism was encountered. Based on their structural characteristics, bixin and norbixin are classified under carotenoid derivatives called apocarotenoids. Bixin is unique among naturally occurring carotenoids not only because of the 9'-*cis* structure containing carotenoid (oxygenated carotenoid like lutein and belongs to the xanthophylls category) but also because the molecule has two carboxylic groups, one of which is a methyl ester. So, it is chemically called as monomethyl ester of a mono-*cis* polyene dicarboxylic acid. (methyl hydrogen 9'-*cis*-6,6'-diapocarotene-6,6'-dioate) with a molecular weight of 394.49. The alkaline hydrolysis of this methyl ester group gives the water-soluble salt of the dicarboxylic acid norbixin ($C_{24}H_{28}O_4$) (Giridhar *et al.*, 2014).

Applications

Preston and Rickard (1980) claimed that for colouring butter, margarine and cheese, in particular, annatto extracts have been employed for several years.

Fleischer *et al.* (2003) discovered that the ethanolic annatto extract from seeds has anti-microbial activity against *Salmonella typhi*, *Escherichia coli*, *Candida albicans*, *Staphylococcus aureus* and other bacteria. The bixin extract inhibited the development of fungus and bacteria. Annatto and other plant components have been found to have wound-healing properties by modern science. Particularly, the anti-oxidant-active seed extract (bixin), which is used in medicine, helps to scavenge the reactive oxidative oxygen species. Bixin, phenolic chemicals and geranylgeraniol are among the ingredients in seed extracts that give them their anti-mutagenic and anti-cancer properties (Júnior *et al.*, 2005). Rao *et al.* (2007) experimented with the usage of water-soluble annatto dye formulations to impart colour to a wide range of extruded foods, including rice and wheat noodles, rice and

sago fryums and baked foods like sugar cones and wafer cookies. A colourant mixture with 15-50 mg of norbixin per kilogram of the product was used to achieve the desired shades of yellow-orange to brilliant orange colour. Scotter (2009) claimed the usage of annatto colourant differs from place to country due to diverse food cultures and laws, although it is also used in sausages, fish, margarine, snacks, dressings, sauces and confections. Kang *et al.* (2010) added that annatto has also been used as a spice in addition to imparting colour. Bixin, a carotenoid that binds to membranes and protects membrane cholesterol, however, did not have this impact (Figueirêdo *et al.*, 2015). The permitted food additives in butter as per Food Safety and Standards Regulations, 2011 for Annatto extract on Bixin/ Norbixin basis (50:50 ratio) is 20 ppm max (FSSAI, 2011).

Sathiya Mala *et al.* (2015) developed the annatto colour compositions and amount of application in a few dairy products (butter, cheese, paneer, biscuit cream, icing cream). Formulations of potassium carbonate that are water-soluble (nor-bixin, 11.24 %), oil-soluble (1.35 %) and both oil- and water-soluble (PG formulation, 1.31% bixin) were made using the dye made from annatto seeds.

Pretreatments

Faria and Rocha (2000) conducted the drying of annatto seeds (*Bixa orellana* L.), a red piave crop, in a fixed bed drier, the ideal circumstances were determined to prevent significant colour loss and to obtain sufficient final moisture in the seeds for quality and colour preservation. For the seeds utilised in this investigation, it was confirmed that the final bixin content is only considerably influenced by the drying period, which is accurately characterized by a linear model.

Prakash *et al.* (2004) investigated the drying characteristics of carrots in a solar cabinet dryer, a fluidized bed dryer (at temperatures 50, 60 and 70 °C) and a microwave oven dryer (at power levels 2, 3 and 4). da Costa Santos *et al.* (2013) experimented with colour extraction, annatto seeds were dried in the current investigation both with and without the excess oil layer. At 40, 50, 60 and 70 °C, seeds were dried. Up to a moisture content of around 5% wet basis, drying was done. At 40 and 50 °C, oil-containing seeds dried more slowly, whereas, at 60 and 70 °C, they dried more quickly.

Bedoya-Corrales *et al.* (2018) explored a novel approach to preserve bioactive compounds bixin in annatto seeds by the use of vacuum as a drying technique.

Extraction Methods

Cunha *et al.* (2009) examined the impact of the distance between the draft tube and the conical base on the mechanical extraction of the bixin from *Bixa orellana* seeds using a spouted bed. For the mechanical extraction of bixin in a spouted bed, the effects of the independent variables (seed charge in the bed, presence and clearing of the draft tube and airflow rate) on the response variables were noted. The outcomes indicated that the variable that most significantly impacted powder extraction was the existence of the draft tube. The situation where the draught tube was placed 4 cm from the air inlet was ideal for the extraction of bixin from *B. orellana* seeds. Raddatz Mota *et al.* (2016) extracted compounds and pigments from seven (42, 43, 45, 46, 47, 48 and 50) Mexican accessions of *Bixa orellana*. The extraction process employed water, 100% ethanol and 2% KOH. With a bixin content of 4.84 per cent, KOH had the greatest amount, followed by ethanol (3.46%) and water (3.37%). The ethanol extract was blacker and more vibrant. The polarity of the solvents utilised was to blame for this. Red was more intense in accession 43 and 50. Bixin concentrations were highest in accession 48 (3.1%), 45 (1.6%), 43 (1.4%) and 47 (1.2%). Total phenolic compounds, tocotrienols and antioxidant capability were all highest in accession 50. Taham *et al.* (2016) used a screen-topped spouted bed apparatus to undertake the mechanical extraction of bixin from annatto seeds. The primary process variables for product yield and purity are seed mass, screen height inside the equipment and air flow rate. Using a differential evolution method, the ideal circumstances for the mechanical extraction were found. The mass of the bixin and powder that were produced, 134.95 g and 47.52 g, respectively, were noticeably higher. The resulting powder has a high purity of 66.2 per cent.

Alcázar-Alay *et al.* (2017) explored the mechanical extraction of bixin from semi-defatted ranged from 1.9 to 6.6 per cent. A maximum bixin concentration ranging from 3.0 to 16.6 per cent was achieved by mechanical fractionation combined with low-pressure extraction. Process factors like the temperature (40, 50 and 60 °C) of annatto seeds using a solvent. The bixin concentration obtained via low-pressure extraction (200 bar), seed-to-solvent ratio (10, 15 and 20) and duration had a substantial impact on the bixin yield. Temperature lowers the concentration of bixin because it makes the other compounds more soluble. The highest concentration of bixin was obtained from mechanically separated seeds after low-pressure extraction.

Ha and Jong-bang (2019) studied the effect of acetone, soybean oil and sodium hydroxide on the extraction of bixin was assessed by adjusting the extraction duration, temperature, solid-liquid ratio and light exposure. On the bixin yield, each parameter had a discernible impact. After 40 minutes of acetone-based extraction, the maximum yield of bixin 68.1% was attained. Low bixin levels were produced using soybean oil and sodium hydroxide. Bixin could be extracted using sodium hydroxide at a temperature of 50°C, it was discovered. Degradation of the bixin content was caused by an increase in time and temperature. Bixin degradation was minimised during extraction by blocking light. More bixin was extracted from the annatto seeds using acetone as a solvent without light incidence.

Sabuz *et al.* (2020) examined soaking, refluxing and soxhlet extraction techniques to extract annatto. The maximum yield of bixin, 8.93%, was obtained after soaking annatto seeds in water for 6, 12, 18 and 24 hours. When compared to the soxhlet approach (7.1%), the reflux method utilising ethyl acetate produced the highest bixin yield (10.1%).

Handayani *et al.* (2021) adjusted the pH (4, 7 and 9) and extraction temperature (70, 80 and 90°C), it was feasible to determine the hue and antibacterial properties of aqueous annatto extracts. Alkaloids, phenols, tannins and saponins were among the phytochemical characteristics that did not significantly alter between the distilled water extracts with various pH and temperatures. Flavonoids were not present in the extracts. At 80 °C and pH 4, *S. aureus* had a maximal inhibition diameter of 49.33 mm. The maximum colour values (7.5), value (6.0) and chroma (10) were obtained at 80°C and 4 pH, but the extract's observance was higher at 70°C and 9 pH.

Stabilization of Bixin

1. Additives

Tood Jr (1992) suggested that adding certain emulsifiers to annatto, tomato, carrot, marigold and synthetic carotenoid pigments significantly increases their stability under oxidative and thermal stress. A synergistic impact was observed when rosemary extracts, tea extracts and tocopherols were combined. The resulting stabilised pigments are many orders of magnitude more stable than the unstabilized pigments, allowing for the replacement of these natural pigments with the synthetic colours now employed in foods where the carotenoid pigments are unstable.

Van Chuyen *et al.* (2012) extracted bixin from annatto seeds by submerging the seeds in acetone and by combining extractions using sodium hydroxide and soybean oil in

the dark to improve extraction yield and reduce the content of volatile compounds in annatto extracts.

Wendy Voon *et al.* (2014) studied the influence of various betel leaf extract concentrations on colour and it was found that when the betel leaf extract concentration was raised, the colour of the homemade chilli bo became darker and stabilized.

Chung *et al.* (2016) investigated the potential role of natural compounds in preserving anthocyanin's vibrant colour in beverages. Natural food colourings called anthocyanins are commonly employed and extended storage could cause them to lose their colour. To determine if they could slow down colour fading, the evaluation of a variety of natural compounds, including quillaja saponin and polyphenols (found in sources such as green tea and vanilla) was employed. The model beverages were prepared with citric acid, l-ascorbic acid and a little amount of purple carrot anthocyanin, then stored in the light for seven days at 40 °C. It was observed that adding polyphenols, particularly green tea extract, slowed down colour fading. Green tea extract increased the amount of time it takes for the colour to fade by 1.9 to 6.7 days.

2. Microencapsulation

Desai and Jin Park (2005) reports that microencapsulation is the process of incorporation of food components, enzymes, cells, or other elements in tiny capsules. The processing industry can use microcapsules to protect sensitive food components, prevent nutritional loss, incorporate unusual or time-release mechanisms into the formulation, mask or preserve flavours and aromas and transform the liquid into easily handled solid components.

Rocha *et al.* (2012) microencapsulated lycopene by spray drying, using a modified starch (Capsul®) as an encapsulating agent and assessed the functionality of the capsules by applying them to the cake. Lycopene concentrations were adjusted to 5, 10 and 15% in a solution with 30% solids. These microcapsules had their encapsulation effectiveness and morphology assessed before undergoing a stability test and being used in cakes. Encapsulation efficiency levels ranged from 21 to 29%.

De Marco *et al.* (2013) utilised maltodextrin and gum arabic as encapsulating agents and examined the durability of microencapsulated annatto extract after spray drying. Maltodextrin and gum arabic were combined in 1:1 weight-to-weight ratio and bixin extract was added to the encapsulating agent in a 1:4 weight-to-weight ratio (core: wall). Through a 0.7 mm nozzle diameter, the spray drying process was conducted at air

temperatures of 180°C in the intake and 130°C in the output. At 25°C, the water activity was 0.17, the water solubility was 72% and the microencapsulation efficiency was 75.69%. In comparison to samples exposed to light, the microencapsulated material maintained in darkness demonstrated five times greater stability.

Balakrishnan *et al.* (2021) microencapsulated annatto extract (ethanol) by spray drying utilizing the modified starch (MS) and gelatine (G) as wall materials. The MS: G ratio of the wall materials ranged from 100:0 to 60:40. With a wall material ratio of 60:40, solvent extract and commercial extract showed the highest encapsulation efficiencies, at 86.18% and 86.37%, respectively. Comparing the encapsulated extract to the non-encapsulated annatto, the former showed greater stability against heat, oxygen and light.

Jiménez-González and Guerrero-Beltrán (2021) reviewed the various processes (extraction, pretreatments of the extract, homogenization of the encapsulated agent, spray drying and stability of the powder obtained) described for producing microencapsulated pigments from various natural sources.

Salbi *et al.* (2021) looked into the impact of coating material composition on the encapsulation of fig powder's physical and chemical properties. Maltodextrin and acacia gum were chosen as coating materials in varied ratios (100% and 75%:25%). 1:1 was the core-to-coating ratio. The high-speed homogenizer was used to prepare the microcapsules for 10 minutes at 10,000 rpm. When compared to other coating ratios, the antioxidant activity was often higher when the coating contained 100% acacia gum in the core. Antioxidant activity and total flavonoid concentration showed a positive connection. The physical characteristics of fig powder are greatly improved by combining a coating agent in a ratio of 75%: 25% and vice versa. All physical and chemical attributes were significantly affected by the maltodextrin-to-gum arabic ratio.

Stability of Bixin During Storage

Glória *et al.* (1995) investigated the manner in which water activity affected the stability of bixin in an annatto extract-microcrystalline cellulose model system during storage at 21 ± 1 °C with or without light and/or air. The model system's water adsorption property was identified. After equilibrium was attained, the samples were held in desiccators with saturated salt solutions with water activities ranging from 0.33 to 0.97, either with or without the presence of air or light. Bixin was found to be more stable at intermediate/higher water activity by comparing half-lives.

Barbosa *et al.* (2005) examined whether bixin could be encapsulated by spray-drying with gum arabic or maltodextrin and the stability in aqueous solution was assessed at 21 °C both in the light and the dark. Lyng *et al.* (2005) reported that the bixin complexed with α -cyclodextrin had more resistance to light and air damage.

Gallardo-Cabrera and Rojas-Barahona (2015) examined the impact of temperature and light on the stability of a norbixin aqueous formulation under controlled circumstances. A xenon lamp set at 1000 W/m² was used to irradiate samples for 6 hours in various concentrations for photostability investigations. To imitate natural storage conditions, samples were subjected to 30°C for 12 months and then analysed to determine the influence of temperature. Spectrophotometry at 455 nm was used to measure norbixin levels during storage following exposure to various circumstances. According to the results of forced photostability tests, samples with a high norbixin concentration (5.58%) did not decompose.

Suhag and Nanda (2017) analysed the impact of storage temperatures (25°C room temperature and 35°C accelerated temperature) and packaging materials (high-density polyethylene and aluminium laminated polyethylene) on the stability of spray-dried honey for 180 days. The stability of ascorbic acid and the glass transition temperature were both negatively impacted by the temperature. At both storage temperatures, powders stored in high-density polyethylene pouches had less hygroscopicity and improved phenolic content, ascorbic acid, antioxidant activity and lowest hygroscopicity.

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PROCESSING AND VALUE ADDITION OF INDIAN JUJUBE: A REVIEW

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1. Introduction:

Indian jujube (*Ziziphus mauritiana*) is an age-old fruit variety within the Rhamnaceae family, native to Southern Asia and Eastern Africa. Its cultivation spans globally and it can grow in diverse environments including semi-arid or arid regions characterized by low rainfall, high temperatures, strong winds and various soil compositions such as limestone, laterite and sandy substrates (Lim, 2012; Singh *et al.*, 2021). Indian jujube cultivation extends across numerous countries worldwide, including Pakistan, India, China, Syria, Burma, Malacca, Malaya, Kazakhstan, Nepal, Australia, Western Sahara, Sri Lanka, Afghanistan, Iran, Kuwait, Qatar, Saudi Arabia and Russia (Khushk *et al.*, 2003).

In India, it can be found in the regions of the Himalayas, Rajasthan, Uttar Pradesh, Punjab, Haryana, Gujarat, Madhya Pradesh andhra Pradesh, Maharashtra, Bihar, Chattisgarh, Tamil Nadu, Karnataka, Assam and West Bengal (Awasthi and More, 2008).

The Indian jujube fruit, characterized as a drupe, varies in shape from globose to ovoid, reaching sizes of up to 6 x 4 cm. Its skin, which is either smooth or rough, exhibits a glossy appearance and ranging in color from yellowish to reddish or blackish. The flesh which is white in color, offers a crisp and juicy texture, with a taste profile ranging from sub acid to sweet, transitioning to a mealy consistency when fully ripe. Enclosed within irregularly furrowed stones are tuberculate seeds containing brown kernels of elliptical shape, measuring approximately 6 mm in length. The fruit undergoes a color transformation from green to yellow to chocolate brown as it matures and ripens (Pareek, 2013). Indian jujube fruits are typically eaten fresh, while Chinese jujube fruits are utilized in various processed forms such as dried, juice, candies, and squashes. Research indicates that Indian jujube possesses antimicrobial, anticancer, antioxidant, wound healing, antihyperglycemic, anti-steroidogenic, immunomodulatory, anti-inflammatory, antidiarrheal, and hepatoprotective characteristics (Dahiru *et al.*, 2010; Goyal *et al.*, 2012;

Najafi, 2013; Verma *et al.*, 2018; Butt *et al.*, 2021; Prakash *et al.*, 2021; Ramar *et al.*, 2022). Due to their high moisture content, Indian jujube fruits are highly perishable and can quickly deteriorate a few days after being harvested (Anjum *et al.*, 2020). So, shelf-life extension of fruit is necessary. Processing of Indian jujube fruits possess to be an important factor for shelf-life extension of the fruit.

2. Nutritional composition and Properties of Indian jujube

Indian jujube is highly valued for its sweetness, sourness and its medicinal benefits. Fully ripe Indian jujube fruits offer significant medicinal benefits which include assisting in reducing blood pressure, treating sore throat and controlling stomach issues and diarrhea infections. (CCS HAU, 2019). The Indian jujube fruits contain protein with many essential amino acids, which include glycine, threonine, glutamic acid, asparagine, serine, arginine and aspartic acid. The pulp of Indian jujube fruit is rich in sugars such as fructose, glucose, sucrose and starch, making it a high-carbohydrate source that offers energy (Bal, 1984).

Indian jujube fruits are abundant in phosphorus, calcium and protein. (Jawanda and Bal, 1978). The fruits also contain higher levels of phosphorus, iron and vitamin C content when compared to oranges. Additionally, it contains more protein, phosphorus, calcium, carotene and vitamin C content when compared to apples (Pareek, 2001).

The fruit contains 0.8% protein, 17.0% carbohydrate, 0.3% fat, 0.02 mg/100g Vitamin A, 0.02mg/100g Vitamin B₂, 76.0mg/100g Vitamin C, 1.8mg/100g iron, 9.0mg/100g phosphorous, 4.0mg/100g calcium and 73.9 Kcal/g energy (Chandra and Gupta, 1994). The fruit pulp contains an acidity level of 0.46 to 0.51% and TSS percentage ranging from 17 to 19%. The pulp to stone ratio is 14 (Azam-Ali *et al.*, 2001). The primary organic acids found in Indian jujube fruit were found to be Citric, malonic and malic acids (Muchuweti *et al.*, 2005).

3. Bioactive Compounds

The jujube fruit is acknowledged as an excellent source of bioactive compounds like polysaccharides, phenolics, flavonoids and saponins, which contribute to several biological functions such as inhibiting cancer cell growth, easing brain nerve disorders, modulating immune function and lowering blood triglyceride levels (Dahiru and Obidoa, 2008; Li *et al.*, 2011)..

The predominant phenolic compounds found in Indian jujube fruit are caffeic acid, *p*-hydroxybenzoic acid, ferulic acid and *p*-coumaric acid (Muchuweti *et al.*, 2005; Koley *et al.*, 2011; Memon *et al.*, 2012) and these compounds contribute to the fruit's notable

antioxidant activity, reducing power activity and free radical scavenging abilities (Kamiloglu *et al.*, 2009; Zhang *et al.*, 2010; Krishna and Parashar, 2013). Twelve commercial varieties of Indian jujube fruit were assessed for their levels of ascorbic acid (AA), total phenolics (TPH), flavonoids (TF) and overall antioxidant activity (AOX). Ascorbic acid content varied between 19.54 and 99.49 mg/100 g, while total phenolics and total flavonoids ranged from 172 to 328.6 mg GAE/100 g and 8.36 to 21.97 mg CE/100 g, respectively. The total antioxidant activity ranged from 7.41 to 13.93 μ mol Trolox/g in ferric reducing antioxidant power (FRAP) and from 8.01 to 15.13 μ mol Trolox/g in cupric reducing antioxidant capacity (CUPRAC) (Koley *et al.*, 2016).

Four species of Indian jujube fruit were assessed for their flavonoid profiles, identifying 12 flavonoids and also comparing three base hydrolysis techniques namely ultrasonic assisted base hydrolysis (UABH), microwave assisted base hydrolysis (MWABH) and pressurized liquid assisted base hydrolysis (PLABH) for quantifying total phenolic acids. Nine phenolic acids were identified, with p-coumaric acid, vanillin and ferulic acid being the major ones across all species. PLABH yielded significantly higher amounts of total phenolic acids compared to UABH and MWABH ($p < 0.05$) (Memon *et al.*, 2013).

The study on *Ziziphus mauritiana* and *Ziziphus nummularia* fruit extracts revealed that both fruits possess antioxidant properties, with *Z. mauritiana* showing higher antioxidant activity. In DPPH and hydrogen peroxide (H_2O_2) scavenging assays, *Z. mauritiana* extracts achieved the highest scavenging rates of 79.5% and 73.4% at 250 μ g/mL, respectively, while *Z. nummularia* extracts showed scavenging rates of 77.5% and 71% at the same concentration (Dureja and Dhiman, 2012). *Z. mauritiana* ethanol extract also demonstrated the highest lipid peroxidation inhibition and superoxide radical scavenging activities with EC₅₀ values of 298.65 μ g and 156.45 μ g, respectively. Phytochemical screening revealed the presence of compounds like cardiac glycosides, polyphenols, resins, saponins and tannins in the plants (Abalaka *et al.*, 2011).

The composition of *Ziziphus mauritiana* mucilage (ZMM) and several properties related to its nutritional quality was studied. The results showed that the *Ziziphus mauritiana* mucilage exhibits potent antioxidant activity against DPPH (5.27 g mucilage/g DPPH), ABTS (16,587.32 mmol trolox equiv./g), hydroxyl (76.13%) and superoxide (85.12%) radicals, which is primarily due to its content of polyphenols (25.54 mg GAE/g mucilage) (Sangeethapriya and Siddhuraju, 2014). In a study, gamma irradiation was used to investigate the effect on the antioxidant properties of Indian jujube fruits. The fruits

underwent irradiation at doses of 0.25, 0.5, 0.75 and 1 kGy and various assays were conducted to assess antioxidant activity. DPPH radical scavenging activity increased from 78.57% to 85.78% in samples irradiated at 1 kGy, while superoxide anion radical scavenging activity rose from 74% to 93.33% at 1 kGy (Kavitha *et al.*, 2015).

A study on the effect of processing on antioxidant properties of Indian jujube fruit was evaluated. Fresh Indian jujube fruits exhibited $78.57 \pm 0.16\%$ DPPH radical scavenging activity, 3.51 ± 0.05 absorbance for reducing power, $74.0 \pm 2\%$ superoxide anion radical activity, $232.84 \pm 3.06\%$ TBARS activity, 94.7 ± 0.27 μg of total phenolic content (PE) and 7.48 ± 0.01 μg of total flavonoid content (RE). Blanching led to an increase in total flavonoid content and superoxide anion radical activity but a decrease in scavenging activity, reducing power and total phenolic content compared to fresh fruit. Processing Indian jujube fruit into RTS beverage resulted in an increase in superoxide anion radical activity, but a slight decrease in scavenging activity, reducing power, total flavonoid content and total phenolic content (Kavitha and Kuna, 2014). The ethanolic extracts of fruit powder were assessed using a DPPH free radical solution, revealing significant antioxidant activities in the fruit extracts. The IC₅₀ values of the ethanolic extracts of Indian jujube (Local) and Indian jujube (Narikeli kul) were 72 and 250 $\mu\text{g}/\text{ml}$, respectively. The local variety exhibited superior antioxidant activity, suggesting that the local variety of Indian jujube is highly beneficial for human health (Bhuiyan *et al.*, 2009).

4. Processing and Value Addition

The primary objective of food processing is to prevent food spoilage during storage, which is often caused by the growth of bacteria, yeasts and fungi. Additionally, it extends the availability of seasonal products for a longer duration. Proper processing of food products enables the preservation of their characteristic sensory attributes and nutritional qualities, thus contributing to human health (Krška and Mishra, 2008). Typically, jujube fruit is collected during autumn and its shelf-life after harvest is quite limited, lasting no longer than ten days under uncontrolled conditions (Zozio *et al.*, 2014). Both dried, fresh, or powdered Indian jujube can be further utilized for processing purposes. Preliminary treatments such as blanching or sulphuring before dehydration enhance the quality of the end product (Azam-Ali, 2006). To preserve the nutraceutical properties of fruits and prevent their deterioration, fruits are transformed into a range of products including fruit powders, jams, jellies, bars, candies, preserves, syrups, squashes and ready-to-drink items (Pandey and Poonia, 2018).

4.1 Dried Indian jujube

Removing approximately 85–88% moisture from fruit or vegetable slices, whether by exposure to sunlight or in a controlled environment such as an oven, is termed drying (CCS HAU, 2019).

The dehydration process of Indian jujube fruits was examined, revealing that there was no significant disparity in the fat content of the fruits between pretreatment and osmo-drying methods. However, the ash content was found to be highest in pre-treated air-dried fruits (0.63 per cent), compared to untreated osmo-dried fruits (0.51 %) and pre-treated osmo air-dried fruits (0.43 %) (KUMAR and NATH, 2002). To produce a high-quality dried product with Indian jujube, it is recommended to immerse the fruits in boiling water for 5 minutes before proceeding with dehydration (Pareek, 1983). Khurdiya and Singh (1975) proposed that after blanching, the fruit should be exposed to sulphur dioxide fumes in a sulphur box, achieved by burning sulphur powder at a rate of 3.5 to 10 grams per kilogram of fruit for 3 hours. Subsequently, the fruits are dried until they reach a moisture content of 15-20%. The dehydrated fruit can be consumed directly or reconstituted in a 10% sugar solution to make a liquid beverage. Additionally, powdered ber fruit can be rehydrated to produce RTS beverages (Kadam, 2001). Jujube powder contained total sugars of 57.38%, with reducing sugars accounting for 36.98% and non-reducing sugars for 20.40%, alongside an ascorbic acid content of 35.17% (Kumar, 2006).

Kumar and Nath (2002) established the preparation method for Chuhura-like products from Indian jujube using osmo-air drying. Umaran jujube underwent pre-treatment with 1% NaOH, citric acid and KMS solutions. Osmotic drying in 30-60°Brix sugar syrup reduced moisture from 84.4% to 48.4%, followed by drying at 52±2°C for 29 hours, yielding a yellow, sweet, chewy product with 12.7% moisture. Water activity was 0.43 and it stored well under 40.0%-56.3% relative humidity. Gupta and Kaul (2011) similarly used osmo-air drying for Chuhura-like product from jujube, with pre-treatment including NaOH, citric acid and KMS. Optimal product, using 70°Brix sugar for 72 hours, was sensory acceptable.

A study evaluated Indian jujube fruit powders from Gola, Umaran and Kaithali varieties for nutritional composition and product development. Powders showed acidity (2.09% to 2.19%), soluble sugars/acid ratio (8.82 to 9.66) and browning (0.08 to 0.09). Nutrient content varied: moisture (5.21% to 5.68%), protein (6.92% to 7.83%), fat (0.99% to 1.07%), fiber (3.52% to 3.91%), ash (4.27% to 4.49%), soluble sugars (19.08% to

20.17%), reducing sugars (3.61% to 3.98%), non-reducing sugars (15.47% to 16.19%). In-vitro protein and starch digestibility ranged from 76.53% to 78.53% and 40.13 mg to 41.80 mg maltose released/g powder. Umran variety Indian jujube fruit powder was chosen for product development. Baked goods scored well, traditional and extruded products accepted up to 30% supplementation, while unfermented beverages up to 20% (Bajaj, 2013).

4.2 Indian Jujube Beverages

Fruit based drinks are gaining attention in the market as people become more aware of the nutritional benefits of fruits (Srivastava *et al.*, 2006). Bal and Randhawa (2005) conducted studies on creating different products from Indian jujube fruits. Their findings suggested that juicy varieties like Sanour-2, ZG-2 and Kaithli can be processed into pulp, which can be used as a primary ingredient for making squash.

Wine was produced using ripe guava and Indian jujube fruit, by fermentation at 30°C. Results indicated that Indian jujube fruit and guava juices with a pH of 4 yielded higher alcohol content than those with different pH levels (Younis *et al.*, 2014). In a study, vitamin C content and overall acceptability of Indian jujube squash was examined. Results indicated that raw Indian jujube contained 84 mg/100g of vitamin C, while Indian jujube squash contained 39.90 mg/100g (Goyal *et al.*, 2008).

An RTS beverage was created by combining Indian jujube and jamun pulp. Various blending ratios were tested: 75% Indian jujube and 25% jamun, 50% of each and 25% Indian jujube and 75% jamun. Additionally, RTS beverages made solely from 100% Indian jujube pulp or 100% jamun pulp were produced. The blend with 25% Indian jujube pulp and 75% jamun pulp received the highest mean scores, followed by the 50:50 blend and the 100% jamun pulp RTS. All blends were deemed organoleptically acceptable. However, the organoleptic scores gradually decreased during room temperature storage, with the RTS remaining acceptable for up to five months (Jakhar and Pathak, 2012). Khurdiya (1980a) evaluated a Ready to Serve beverage made with 33.3% juice derived from dried Indian jujube fruit, which was cooked and then juiced using a basket press.

4.3 Indian Jujube Candy

The candying of Indian jujube was standardized by Singh *et al.* (1944). Storage trials revealed that LDPE film provided better preservation compared to glass and plastic jars when packaging Indian jujube candy at room temperature. After a storage period of 9 months, the candy remained in good condition when stored in LDPE film (Singh and Pathak, 2016).

Indian jujube candy was produced from 'Umran' variety using the slow syruing technique. Mature Indian jujube fruits were punctured, blanched in hot water for 5 minutes and then subjected to 2g/kg sulphur fumigation for 2 hours (Kaikadi *et al.*, 2006). Similarly, Take and Bhotmange (2012) produced candy from Indian jujube fruits. Mature pricked Indian jujube fruits were cleaned and treated with sodium metabisulphite before undergoing blanching. Findings indicated that candy treated with sodium metabisulphite received higher scores compared to those blanched with hot water.

4.4 Indian Jujube Preserve

Ripe fruits are suitable for creating a preserve, commonly referred to in India as murabba. Varieties such as Umran, Banarsi, Karaka and Kaithli are preferred for making this preserve (Pareek, 2001). The method for making Indian jujube murabba was standardized. Fully ripe Indian jujube fruits were blanched in boiling water for 6 minutes, then rinsed in cold water. The fruits were peeled, pricked and optionally destoned using a cork borer. Murabba prepared in this manner could be easily stored for up to a year (Khurdiya and Singh, 1975). The overall acceptability and vitamin C content of Indian jujube preserve was examined. It was noted that while the raw Indian jujube contained 84 mg/100g of vitamin C, the Indian jujube preserve had a recorded content of 50.83 mg/100g (Goyal *et al.*, 2008).

4.5 Indian Jujube Jam

Jams are widely favored fruit preserves, known as conserves, which are made from whole fruit, fruit pieces, pulp, or puree, sometimes combined with fruit juice or concentrate. They typically incorporate fruit juice along with a carbohydrate sweetener, sometimes with water and are processed to achieve the desired texture (Ranganna, 1986). The quality of Indian jujube and pineapple jam over a storage period was evaluated for their significant nutritional and medicinal value by Sucharitha *et al.* (2012). A gradual decrease in both ascorbic acid and calcium content was observed in the Indian jujube jam over time (Dubey *et al.*, 2014). The overall acceptability and vitamin C content of Indian jujube jam was examined. The raw Indian jujube was found to contain 84 mg/100g, while the Indian jujube jam exhibited a recorded content of 27.32 mg/100g (Goyal *et al.*, 2008).

Conclusion:

Indian jujube is an ancient fruit that has been cultivated globally due to its ability to grow in diverse climates including arid and semi-arid regions. It holds significant economic and nutritional value. As a perishable fruit, various processing techniques have been developed and utilized to extend the shelf-life of Indian jujube and make it available

throughout the year. Drying and production of value-added products are common preservation methods. Proper processing helps retain important phytochemicals and antioxidants in the fruit which contribute to its various health-promoting properties. Further research on novel processing techniques could optimize nutrient retention and explore new product formulations. As consumption of Indian jujube rises due to growing health awareness, its processing industry is expected to expand. Standardization of protocols and commercial scale production can boost Indian jujube processing. Overall, with diverse adaptations and applications, processing plays a vital role in utilizing the full potential of this drought-resistant superfruit and meeting domestic and international demands all year round.

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METHODS OF EXTRACTION OF ANTHOCYANIN FROM ROSELLE CALYX AND APPLICATION AS BIO-COLOURANT: A REVIEW

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Introduction:

Hibiscus sabdariffa. L, so-called roselle belongs to the Kingdom: Plantae, Sub-kingdom: *Tracheobionta*, Division: *Magnoliophyta*, Order: *Malvales*, Family: *Malvaceae*, Genus: *Hibiscus*, Species: *Hibiscus sabdariffa* L. Roselle (*Hibiscus sabdariffa*. Linn.) (Lema *et al.*, 2022b). The plant appears to be bushy and the edible part is the calyx and also grown for its leaves and fibre from the stems. The roselle calyx and plant are provided in Fig.1 and 2. India is considered the largest exporter of roselle to Sudan (Mohamed, 2021). They are classified broadly into two varieties, *H. sabdariffa* var. *sabdariffa* and *H.sabdariffa* var. *altissima* west in many countries around the world (Lema *et al.*, 2022b). The yield for 13,000 to 14,000 kg/ha of fresh calyxes, which in turn gives 1,800 to 2,000 kg/ha of dried calyxes and a seed yield of 2,500 to 3,000 kg/ha can be obtained under Indian climatic conditions.



Figure 1: Roselle Calyx



Figure 2: Roselle Plant

Anthocyanin Content Structure and Stability

These calyces of roselle are rich in anthocyanins, especially iso-anthocyanins. (Bala *et al.*). The calyx portion has many bioactive compounds including vitamins (e.g. ascorbic acid), anthocyanins (e.g. cyanidin-3-O-sambubioside and delphinidin-3- O-sambubioside), flavonoids (e.g. kaempferol, quercetin, apigenin and luteolin), phenolic acids (e.g.

protocatechuic acid and chlorogenic acid) and organic acids (e.g. hibiscus acid and citric acid) (Riaz and Chopra, 2018). Anthocyanins serve two functions primarily, as a natural colourant, which also contains biological actions as antioxidant, antibacterial, antihypertensive and antidiabetic (Borrás-Linares *et al.*, 2015), (Chumsri *et al.*), (Duke, 1993). They have antioxidant activity that has proven to prevent chronic diseases such as cancer and metabolic diseases (Mohamed, 2021), (Adeyi *et al.*). The calyx of roselle is a source of a large anthocyanin reserve; therefore, the more bioactive compounds are used in industrial applications (Adeyi *et al.*). The remarkable fact is that the anthocyanin and major pigments of anthocyanin account for 70-80 % of all natural colouring compounds used in cosmetics, food and textile colourants (Abou-Arab *et al.*, 2011). In recent research, (Lema *et al.*, 2022b) the use of anthocyanins can play a major role in preventing diseases related to lifestyle, including hyperglycemia, neurological and cancer problems, antioxidants and anti-hypertension among others (Shruthi *et al.*, 2016) and (Elhefian).

Today, the most commonly used dyes in the industry are artificial. However, ecological and sustainable concerns have led to more efforts to replace them with safer and more sustainable natural dyes (Shruthi *et al.*, 2016). In the Europe and United States, artificial food colours such as Ponceau 4R (E124) and carmoisine (E122) have been restricted, while natural colourants obtained from the calyces of Roselle (*Hibiscus sabadariffa*. L.) have been suggested (Shruthi *et al.*, 2016). The classification of natural dyes is based on their origin, chemical structure and method of use. However, since chemical structure uniquely identifies dyes as belonging to a certain chemical group with specific qualities, classification based on chemical structure may be more appropriate (Lema *et al.*, 2022b).

Hibiscus sabadariffa. L is a plant native to tropical regions of Africa and Asia. Plant dyes, animal/insect dyes and mineral dyes are biodegradable and more environmentally friendly (Mahadevan and Kamboj, 2009). The anthocyanin content of roselle calyx leaves can be evaluated by various methods, from traditional to advanced methods (Eksiri *et al.*, 2022). After harvesting, the calyces were manually dehulled by using a hand tool that separates the bud and the calyx then dried on racks for 5 to 10 days (Abdel-Moemin, 2016). After 30 minutes of soaking, the calyx powder was soaked in water at a ratio of 1:9 then the extract was obtained and then filtered (Achir *et al.*, 2019). Old colourimetric assays based on pH differences were commonly used to quantify anthocyanins. In this method, the extract has the absorbance which was measured at different pH levels and the anthocyanin

content found from roselle calyx was calculated from the difference in absorbance (Eksiri *et al.*, 2022). Although colourimetric assays are simple and cost-effective, colourimetric assays can lack specificity and accuracy, especially in complex matrices such as roselle goblet, where other pigments and compounds can confound the measurement (Ghodke and Mane, 2017).

One powerful tool for anthocyanin analysis is the HPLC, offering greater specificity and the ability to separate individual compounds. Using appropriate standards and optimized chromatographic conditions, HPLC enables accurate quantification of anthocyanins in roselle calyx extracts (Li *et al.*, 2022). The recent advancements in analytical techniques such as ultra-high performance liquid chromatography coupled to mass spectrometry (UHPLC-MS) improve sensitivity and resolution, enabling the identification and quantification of a wider range of anthocyanin derivatives and related compounds (Yang *et al.*, 2022). The advanced analytical methods when combined with the advanced techniques can provide a comprehensive understanding of the composition and concentration of anthocyanins in roselle calyces, facilitating its use in various applications (Du and Francis, 1973). The advancement such as the integration extraction methods such as the integration of PAE with other extraction methods, such as ultrasonic extraction or enzyme-assisted extraction, promises to improve anthocyanin extraction efficiency and reduce processing time (Ndong *et al.*, 2018).

Chemical Compounds and Composition

Anthocyanin acts as potassium (K) or sodium (Na) salt in alkalis, is soluble in water and has considerable bioavailability in water-based formulations. It is very unstable and very easy to degrade (Giusti and Wrolstad, 2003). The other factors that affect them are storage temperature, pH, chemical structure, oxygen, concentration, light, presence of enzymes, solvents, flavonoids, proteins and metallic ions (Arueya and Akomolafe, 2014). The anthocyanin degradation may also result in the production of aldehyde substances with benzene rings that can affect human health (Mahadevan and Kamboj, 2009). It accounts for the total pigment content of 70% in the roselle calyx. The principal pigments found in roselle calyx are cyanidin-3-sambubioside, cyanidin-3-glucoside, delphinidin - 3glucoside, Cy 3-xylosylglucoside, Dp 3 -xylosylglucoside, Cy 3- glycoside, Dp 3- glycoside which is brilliant red (Al Snafi, 2018) and contains up to 1.5 – 2.5g/100g dry weight of roselle calyces (Yang *et al.*, 2022) which is 150 mg/100g content (Lema *et al.*, 2022b).

Extraction Methods

The separation of the soluble part and the insoluble part (residue) is the main objective of the extraction method (Soumya *et al.*, 2019). The pigment is taken from the dried calyx by various methods from traditional to modern methods which are inexpensive and environmentally friendly (Sarkar *et al.*, 2012). Certain methods which include Microwave-assisted extraction (MAE), Soxhlet extraction, Accelerated Solvent Extraction (Chongwilaikasem *et al.*), Ultrasound-assisted extraction (UAE), Maceration, enzyme-assisted extraction, Microwave-assisted extraction (MAE), Supercritical fluid extraction (SFE), Pulse electric field extraction, Pressurized Liquid extraction etc.(Sharif *et al.*, 2014),(Soumya *et al.*, 2019), (Djaeni and Utari, 2019). The important factor in determining the solubility and extraction efficiency of the target compound is the property. Based on the type of extraction, solvent and temperature used, water-soluble dyes (anthocyanins) can be obtained (Enaru *et al.*, 2021).

Conventional Solvent Extraction

Conventional solvent extraction is considered the usually employed and oldest method for obtaining anthocyanins from roselle calyces and the common extraction of anthocyanins from roselle is nonselective and produces impressive amounts of by-products, such as sugars, natural acids, alcohols, natural acids, proteins and amino acids (Rizkiyah *et al.*, 2023). Different solvent systems are employed, including ethanol-water mixtures (20-80% v/v), methanol-water mixtures and acidified water (Idham *et al.*, 2023). To the extracted solvent the addition of acid has proven crucial for maintaining anthocyanin stability by preserving the flavylium cation form of these compounds (Villalobos-Vega *et al.*, 2023), (Hapsari and Setyaningsih, 2021),(Boukerche *et al.*, 2024) and (Rambe *et al.*, 2022).

Anthocyanin is a non-polar chemical with a stronger affinity for polar solvents like ethyl acetate, acetone and methanol, ethanol, For instance, (Ademiluyi and Oboh, 2013) had used ethyl acetate, alcohol, acetone, 1, 2,-dichloroethane and chloroform. In another study, (Tounkara *et al.*, 2014) a mixture of solvents like chloroform (75:25, v/v) and ethanol was used to extract the aril of roselle calyx. According to the research of (Abou-Arab *et al.*, 2011) (Hinojosa-Gómez *et al.*, 2020).

Super Critical Fluid Extraction

The supercritical extraction using CO₂ is employed here (Putra *et al.*, 2023) (Idham *et al.*, 2023), (Rizkiyah *et al.*, 2023), (Idham *et al.*, 2017), (Lukmanto *et al.*, 2013). The

efficiency of the extraction is improved by adding CO₂ modified with other mixed chemicals (methanol, acetonitrile and chloroform) (Arueya and Akomolafe, 2014),(Pimentel-Moral *et al.*, 2019). Compared to the other conventional extraction methods, the usage of supercritical CO₂ at different pressures and temperatures for the extraction of natural food colours from roselle calyx has shown to be more efficient (Chew *et al.*, 2024), (Rizkiyah *et al.*, 2022).

Some advanced techniques such as Low-Pressure Solvent Extraction (LPSE) and Pressurized Liquid Extraction (PLE) in terms of pressure, temperature, solvent-to-feed ratio, with or without sonication and solvent type were investigated by (Sanou *et al.*, 2023). PLE using ethanol as the solvent produced the highest yield of anthocyanin per mass of calyces (Selim *et al.*, 2008).

Microwave Assisted Extraction (MAE)

MAE also requires less solvent, making it a more environment-friendly extraction method, which is beneficial for green extraction techniques and has emerged as an efficient and innovative method for anthocyanin extraction from Roselle (*Hibiscus sabdariffa* L.) calyx (Pimentel-Moral *et al.*, 2019). The lower temperatures and shorter extraction times help preserve the bioactive components of anthocyanin, which are sensitive to heat and oxidation (Hapsari and Setyaningsih, 2021).

The Microwave-Assisted Extraction (MAE) can significantly outperform traditional methods, yielding 28-35 mg/g dry weight compared to 18-25 mg/g. The technique also reduces extraction time by 85-90% and solvent usage by 40-50% (Hapsari and Setyaningsih, 2021). The main compounds of interest are cyanidin-3-sambubioside and delphinidin-3-sambubioside, which contribute to the characteristic deep red colour of the plant and its medicinal properties (Setyawan and Kartini, 2023b) and (Sartini *et al.*, 2020).

Pressure Assisted Extraction

Pressure-assisted extraction (PAE) is an innovative and efficient technique for anthocyanin extraction, offering various advantages compared to other conventional extraction methods that typically operate at pressures ranging from 100 to 600 MPa, which significantly improves mass transfer and cell wall permeability, thereby improving the extraction efficiency of bioactive compounds (Liu *et al.*, 2024).

Ultrasound-Assisted Extraction (UAE)

Extracts from white and red varieties of *H. sabdariffa* are obtained by ultrasound-assisted extraction (UAE), with intermediate values in terms of yield, antioxidant and

antigenic activity. This has the benefit of using common and easily accessible ultrasonic equipment (water bath), ethanol as solvent and a relatively short extraction time (Rosalinda *et al.*, 2024),(Pinela *et al.*, 2019). Optimization of UAE parameters plays an important role in achieving maximum efficiency of the extract (Ahmed *et al.*, 2023) and (Larasati *et al.*, 2023). Key parameters include ultrasonic power (typically 200–500 W), frequency (optimally 35–45 kHz), extraction time (15–30 min), temperature (30–50 °C) and solvent/material ratio (20: 1 to 40: 1) (Rosalinda *et al.*, 2024), (Aneke *et al.*, 2023).

Combined Extraction Techniques

A novel extraction method that combines subcritical water extraction (SWE) and supercritical carbon dioxide (ScCO₂) has been improved to optimize the recovery of total anthocyanin compounds (TAC) from roselle (Rizkiyah *et al.*, 2023).

Membrane Separation method

Membrane separation technology relies on changes in molecular weight to effectively separate impurities from target compounds. Currently, the membranes used for crude separation and extraction primarily include microfiltration (Al-Ansary *et al.*), ultrafiltration (Yusoff *et al.*) and nanofiltration (Li *et al.*) membranes.

Stability Studies of Anthocyanin

Colour Stability

Water-soluble pigments, such as anthocyanins, present in plants such as Roselle (*Hibiscus sabdariffa*. Linn), are accountable for creating shades of red, purple and blue(Zannou *et al.*, 2020). They are recognized for their ability to serve as natural food dyes because of their bright colours and antioxidant benefits (Wu *et al.*, 2018). Nevertheless, their application in the food sector is restricted because of their vulnerability to various environmental factors like light, heat, pH fluctuations and exposure to oxygen. (Cavalcanti *et al.*, 2011). The anthocyanins are mostly relied on the aqueous phase of pH.

pH Stability

Roselle primarily contains anthocyanin derivatives of cyanidin, specifically cyanidin-3-O-glucoside and cyanidin-3-O-sambubioside. The mentioned compound varieties are more sensitive to pH changes. At low pH (1-3), they show a bright red colour due to the presence of flavylium cation in the most stable form (Duangmal *et al.*, 2008). According to (Setyawan and Kartini, 2023b) the anthocyanin pigments which showed higher pigment retention at pH 1 and pH 2 and the colour observed was more vibrant amongst the pH range. However, as the pH increases, they transform into less stable forms,

such as quinoidal bases and chalcones, leading to colour changes from red to blue or colourless (Cavalcanti *et al.*, 2011).

Light Stability

In addition to pH and temperature, exposure to light, particularly UV radiation, can lead to the photodegradation of anthocyanins. Light stability is the one where it is an important aspect of anthocyanin during storage conditions and in a study conducted by (Sipahli, 2017) the HCl sample appeared to be the least degraded sample compared to other samples. To prevent this degradation, it is important to use packaging materials that block or filter light (Lema *et al.*, 2022). Light triggers oxidation reactions, causing anthocyanin molecules to break down and result in noticeable discolouration (Cavalcanti *et al.*, 2011).

Temperature Stability

The research conducted by (Sipahli, 2017) shows that the extracts that are treated at 80 and 50° C for 6 hours and the acetic acid have the most consistency of pigment retention over both heat treatments (Manjula *et al.*, 2018). Heat processing can trigger various mechanisms that affect anthocyanins, including glycosylation, nucleophilic water attack, cleavage and polymerization. These reactions can help in leading ahead to the degradation of anthocyanins and result in the loss of this pigment (Zuluaga-Vega *et al.*, 2024) and (Wu *et al.*, 2018)

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BIODEGRADABLE PLASTIC MULCH AND ITS DEGRADATIVE IMPACT ON SOIL ECOSYSTEM

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Abstract:

Biodegradable plastic mulch (BPM) has gained significant attention as a potential solution to reduce the environmental impact of conventional plastic mulch in agriculture. This abstract explores the use of BPM and its consequences on soil ecosystems. BPM is designed to break down into harmless components, eliminating the need for removal after crop cultivation. However, the degradation process raises concerns about its effects on soil health and the broader ecosystem. This review investigates the biodegradation mechanisms of BPM, such as microbial activity, temperature and moisture and how they influence soil structure, nutrient cycling and microbial communities. We also delve into the potential benefits and drawbacks of BPM adoption in agriculture, including reduced plastic waste and potential soil quality improvements, as well as potential issues like microplastic pollution and alterations in soil biodiversity. Additionally, we discuss current research gaps and the need for comprehensive, long-term studies to assess the true impact of BPM on soil ecosystems, enabling informed decisions for sustainable agriculture practices.

Keywords: Biodegradable Plastic Mulch, Soil Ecosystem, Microbial Activity, Soil Quality.

Introduction:

Plastic mulch is a commonly used agricultural practice that involves covering the soil surface with a plastic film to suppress weeds, conserve soil moisture and increase crop yields. Conventional plastic mulches are made from polyethylene, which is a non-biodegradable material that can take hundreds of years to break down in the environment. This has led to concerns about the environmental impact of plastic mulch, including the potential for microplastic pollution and the accumulation of plastic debris in soil and water bodies. Biodegradable plastic mulches (BDMs) are an emerging alternative to conventional plastic mulches that are non-biodegradable and have limited recycling options. BDMs are made from materials such as starch, cellulose and polylactic acid (PLA). Biodegradable plastic mulches are an alternative to conventional plastic mulches that are designed to decompose into natural products, such as carbon dioxide, water and biomass, over a

relatively short period of time. Biodegradable plastic mulches are often made from materials such as starch, cellulose and polylactic acid (PLA) which are expected to be broken down by soil microorganisms over time.

The degradative impact of biodegradable plastic mulch on soil ecosystems is a complex issue that is not fully understood. Some studies have shown that biodegradable plastic mulch can have positive effects on soil health, such as increasing soil organic matter content and microbial activity. Other studies have shown that biodegradable plastic mulch can have negative effects on soil health, such as reducing soil water infiltration and increasing soil compaction. The degradative impact of biodegradable plastic mulch on soil ecosystems is likely to vary depending on a number of factors, such as the type of biodegradable plastic mulch used, the soil conditions and the management practices used. More research is needed to better understand the long-term effects of biodegradable plastic mulch on soil health.

Biodegradable Mulch Ingredients (Brodhagen *et al.* 2015)

Ingredient	Feedstock	Polymer synthesis	ERBD in soil
Cellulose	Biobased	Biological	High
PBAT	Hydrocarbon	Chemical	Low moderate
PBS	Hydrocarbon	Chemical	Low moderate
PBSA	Hydrocarbon	Chemical	Low moderate
PCL	Hydrocarbon	Chemical	Moderate
PHA	Biobased	Chemical	Moderate high
PLA	Biobased	Biological and Chemical	Low
Sucrose	Biobased	Biological	High
TPS/Starch	Biobased	Biological	High

Abbreviations: PBAT: Polybutylene adipate terephthalate, PBS: Polybutylene succinate, PBSA: Poly (butylene succinate adipate), PBS: poly (butylene succinate) PCL: Polycaprolactone, PHA: Polyhydroxyalkanoate, PLA: Polylactic acid, TPS: Thermoplastic starch

Benefits of Biodegradable Plastic Mulch

- ❖ The biodegradable plastic mulches incorporation into soil can help to enhance bacterial and fungal activity.
- ❖ Degrade/decompose in situ and release nutrients
- ❖ Unnecessary to remove them
- ❖ Adjusted to the shelf life to the crop cycle

- ❖ Reduce the labor costs for removal and disposal
- ❖ Reduce the landfill waste
- ❖ Biodegradable completely
- ❖ Causes no harm to soil ecology or environment
- ❖ Prevent soil contamination by not producing toxic waste after use

Degradation of Biodegradable Plastic Mulch (BDMs)

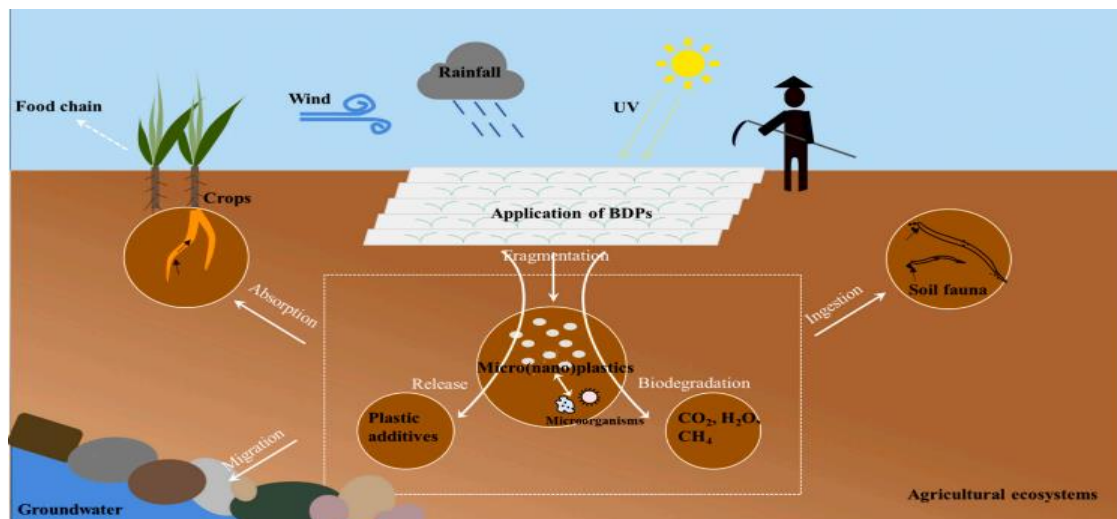


Figure 1: Environmental fate of BPMs in agricultural soil (Aoyun *et al.* 2023)

Decomposition is a crucial process to determine the fate of BDPs in agricultural soil. In fact, BDPs can hardly be completely degraded into final products of CO₂ and H₂O in one step. The decomposition process of BDPs usually included fragmentation and biodegradation. BDPs film and other productions were firstly fragmented by action of solar radiation, water erosion, wind action, earthworms, crop growth and bioturbation and produced smaller plastic residues. Then, plastic residues were further degraded into end products by soil microorganisms. The crux of the degradation of BDPs is breakage of chemical bonds in the polymer. Within polymer molecule of BDPs, weak or easy reacted chemical bonds were readily degraded. Four types of cracking molecular chain were suggested in this process, including.

Depolymerisation, fragmentation type, weak bond separation and side chain or small molecule detachment. In general, the hydrolysis process, *i.e.*, depolymerisation into oligomers and monomers was considered as a rate-limiting step in the degradation of BDPs. In the process of microbial hydrolysis, natural microorganisms such as soil bacteria, fungi and algae utilized relative enzymes to catalyze the scission of polymer chains of BDPs and presented surface erosion or bulk erosion. According to Aoyun *et al.* (2023), bulk erosion occurred uniformly on the surface and inside of the polymer. The hydrolysis

reaction was firstly initiated by the diffusion of water in the amorphous region of BDPs. After that, oligomers would slowly diffuse to the polymer surface. On the contrary, surface erosion only appeared on the polymer surface, of relatively low erosion rates in comparison to bulk erosion. Hydrophobic and semi-crystalline polymers had relatively fast hydrolysis rate.

The degradation efficiency of BDPs in soil would largely depend on the composition and structure of polymers. Polymers with natural or natural-like structures were proved to easily degrade by soil microbiome and starch- or cellulose-based BDPs and microbially metabolized synthetic polymers such as PHA were highly degradable. In addition, aliphatic polyesters with single linear chain structures were more degradable than aromatic polyesters containing benzene rings; aromatic polymers were less likely destroyed by soil microorganisms. Tightly packed crystalline regions of polymers usually hindered enzymatic attack and were proved to hardly decompose. Oppositely, highly flexible polymer chains fit more closely to the active site of enzymes were highly biodegradable. In addition, microbial communities are crucial to degrade BDPs, lots of environmental factors including soil temperature, humidity and oxygen content would influence degradation efficiency due to their impacts on reproduction of soil microbiome). Previous studies have shown microbial activity enhanced with the increase of soil temperature under BDPs mulching treatment. But microbial activity would be inhibited when the soil temperature was higher than optimum temperature of soil microbiome and reduce the degradation of BDPs.

Mesofauna have a high opportunity to ingest BDPs residuals in topsoil and induce adverse effects. Earthworms were usually considered as an important biological indicator for soil quality and ecological health (Zhang *et al.*, 2016; Zhang *et al.*, 2022c). According to results of standard biotoxicological tests, earthworm's biomass and reproduction declined after exposure to PLA and PPC MPs of higher than 40 g/kg, which showed a relatively strong impact on earthworms in comparison to the same exposure of conventional MPs. If merely considering this result, the advantage of BDPs of environmentally friendly is somewhat doubtful. Similarly, found that earthworm biomass decreased after soil exposure to BDPs in spite of no significant change in survival rates of animals. In addition, earthworms can in turn affect the degradation of BDPs in soil, as earthworms were proved to carry BDPs mulch fragments into deep soil layers, or take up and then excrete small plastic debris in composted soil condition, thus accelerate the degradation of BDPs (Zhang *et al.*, 2016).

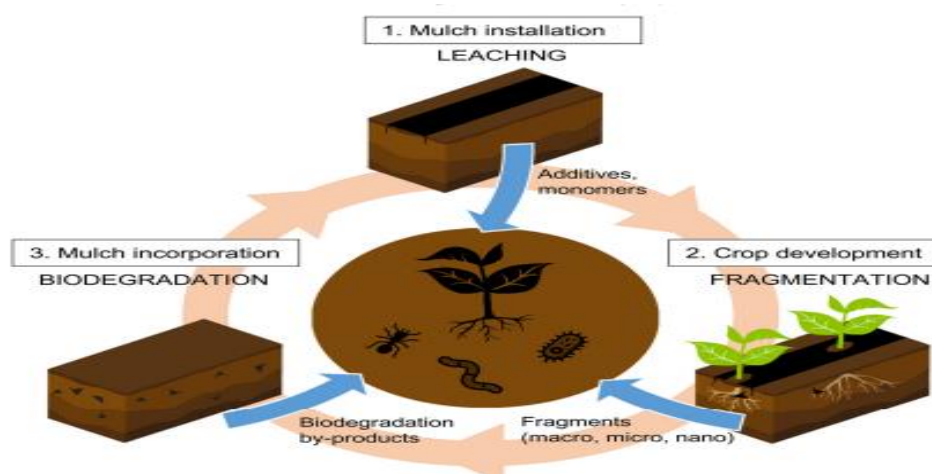
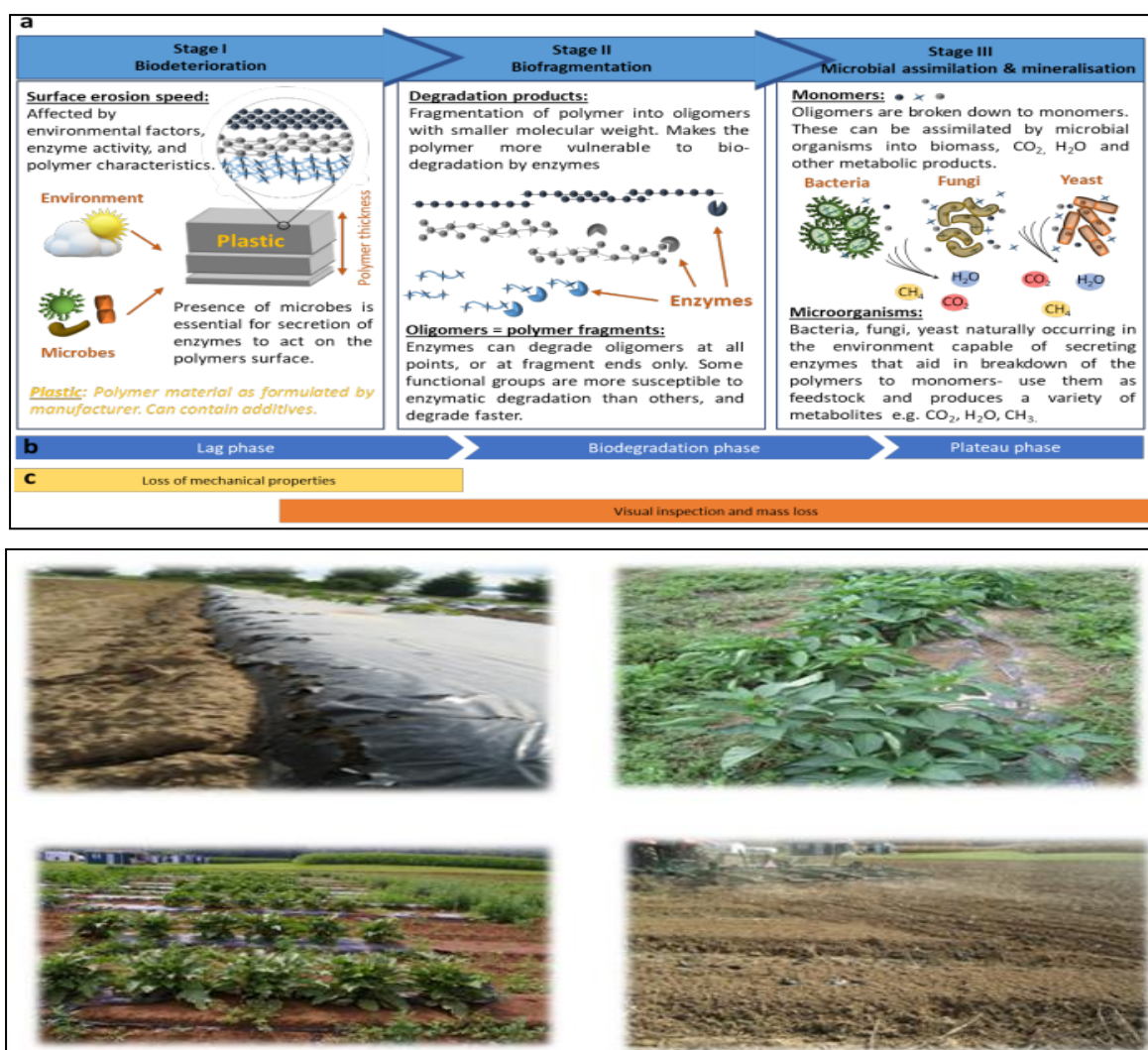


Figure 2: Agricultural cycle of biodegradable plastic mulch films during time of use (Hadaly *et al.* 2021)

The degradation of BDPs mulch in the soil is mainly carried out by certain species of soil microbiome. In turn, the degradation process can likely change the structure and quantity of microbial communities in surrounding soil. According to a recent study, BDPs had an impact on microbial abundance and related enzyme activity in soil, which would be due to the fact that the degradation of BDPs cause the release of monomers that were used by microorganisms as exogenous organic matters, resulting in an increase in microbial biomass. Moreover, mulch treatment of BDPs could induce change in water content and soil temperature, which would accelerate the growth and development of plant roots thereby affecting microbial and enzyme activities (Li *et al.*, 2014). Another study disclosed an increase in the abundance of both bacteria and fungi in the soil after the mulch treatment of BDPs, but without significant effects on the enzyme profile within soil (Bandyopadhyay *et al.*, 2020), which suggests that the function of the soil microbial community was not significantly influenced by BDPs. However, according to Qi *et al.* (2020b), the abundance of some specific bacterial genera (*e.g.*, *Bacillus*, *Omni bacterium* and *Clostridium*) in the inter-rhizosphere bacterial community were significantly increased after BDPs mulch fragments were buried in the soil for 4 months, but the abundance of other bacterial genera decreased, presenting different effects of size-different mulch fragments. Similarly, another study showed that burying treatment of BDPs mulch fragments for seven months caused an increase in the abundance of soil fungal and bacterial communities, especially the fungal plant pathogen *Setophoma terrestris*. In addition, Zhang *et al.* (2022a) demonstrated that soil microbial activity, urease activity and peroxidase activity were significantly increased after BDPs mulching treatment in soil.

Biodegradable plastic mulch is primitively designed to be later integrated into soil, where native microorganisms can fully consume these polymers. Assumed conception of BDPs mulch is to avoid generation of long-term residue of plastic fragments after full biodegradation. However, the practical degradation of BDPs mulch is complex in agricultural soil. In the process of biodegradation, soil microbiome, mainly bacteria and fungi, are firstly colonized on the polymer surface, then generate extracellular enzymes to depolymerize polymers and finally consume the hydrolysis products of BDPs. Soil microorganisms would interact with plastic residuals within the surrounding soil. BDPs may generate lots of MPs and Nano plastics (NPs) and release chemicals including monomer and additives, which could further enter into crops and soil animals. The detailed fate of BDPs within agricultural ecosystems is summarized in Fig 2.

Different Degradation Stages of Biodegradable Plastic Mulch



(Corbin *et al.* 2013)

Stage 1: Abiotic-Deterioration and Biotic-Deterioration

This is the initial stage at the end of the plastics useable lifetime where the plastic begins to lose its physical and structural properties. It can be tested quantitatively by changes in the tensile and elastic strength and brittleness of the material. Most initial degradation mechanisms can be considered abiotic, as they involve physical and chemical actions but not biological actions. They are a combination of several factors.

- **Mechanical degradation:** Physical forces acting to damage plastic. Compression, tension and shear forces such as air and water turbulence, snow pressure, animal tearing etc.
- **Light degradation (also referred to as photo-degradation):** UV-radiation from the sun (or artificial light source) initiates chemical reactions to destabilise polymers.
- **Thermal degradation (Thermooxidative):** Exposure to heat influences the organised framework of polymers.
- **Chemical degradation:** Exposure to chemicals such as atmospheric pollutants or agrochemicals can lead to a breakdown. Oxygen in the atmosphere is one of the most important factors to oxidative degradation of polymers and dependent on the type of plastic, can disrupt several types of chemical bonds.

Biotic-degradation is defined as the breakdown of the polymer from the action of biological reagents *i.e.* enzymes from microorganisms. Often, both the abiotic and biotic mechanisms act synergistically to break down a polymer, but many plastics are inherently biologically un-reactive. These rely on the initial abiotic (mechanical) degradation to facilitate the next stage of biodegradation and may require other reagents (see below in section 5 for further discussion regarding additives) to speed up chain reactions of fragmentation. Once a polymer is broken into smaller fragments (oligomers) it is often more vulnerable to biotic degradation as described in above figure. In plastic degradation studies, heat exposure and UV-light are frequently used at exaggeratedly high levels to speed up the mechanical abiotic degradation before testing the biodegradation time scale. This artificial pre-treatment can vary between studies and affects the final results. Unfortunately, Exposure to conditions found in nature means a study would take years to complete. The rate of the initial breakdown also depends on many other factors including (but not limited to) the polymer chain length, crystallinity, molecular weight distribution, the size, shape and geometry of particle, the surface porosity, pore size and distribution, pore geometry and water diffusivity in the polymer matrix - all of which are function of the polymer's manufacturing process.

Stage 2: Bio Fragmentation

As mentioned, once a plastic polymer fragments into shorter chains (oligomers), it becomes more vulnerable for enzymatic (*i.e* bio) 'attack'. The bioavailability of the material increases as it is both physically and chemically more accessible to the action of microorganisms and the enzymes secreted by them. The enzymes can be released to their surrounding environments by microorganisms to work directly on the polymers, or the microorganisms may rely on abiotic factors to break the polymer into sufficiently small pieces to allow them to enter the cell to be hydrolysed by internal enzymes. The rate of breakdown depends on the nature of the polymers. Linear non-reactive fragments will be harder for the enzymes to access and disrupt, compared to polymers with several functional groups that present a handle for the enzymes to act on. Another rate-determining factor is the quantity of enzyme available, which in turn depends on the microorganisms present. This is further discussed below, but put simply, the more microorganisms that can degrade the plastic, the faster it will degrade.

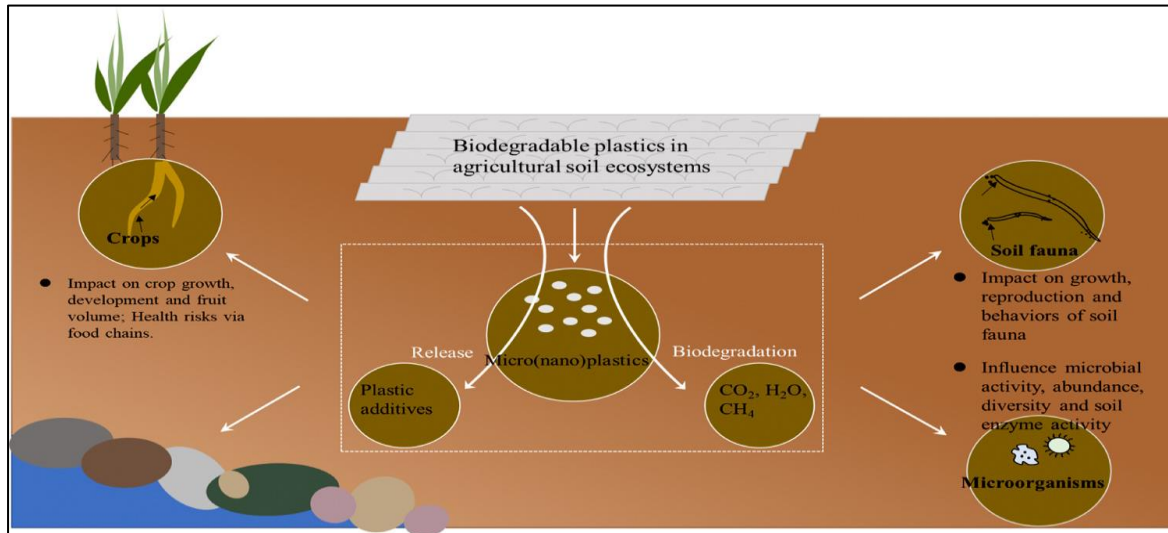
Several studies suggest that bio augmentation (addition of more microorganisms) targeted to enhance the rate of biodegradation and a range of microbial hosts have been identified as of degrading plastics such as PLA, LDPE, PET and several other polyesters. The fragmentation stage can be difficult to assess in a quantifiable manner and is mainly tested for by visual inspection such as microbial attachment to plastic fragments, or by mass loss. The visual inspection typically requires a microscope and computational analysis to avoid bias. As more polymers are hydrolysed, gases begin to develop and can be detected and quantified to indicate the final stage of degradation. One major problem is that the mechanical breakdown of plastic while leaving the polymer more vulnerable to microbial degradation can also result in the formation of potentially non-degradable micro-fragments known as micro plastics.

Stage 3: Microbial Assimilation and Mineralisation

This stage can be viewed as the microorganism "eating" and "digesting" the polymers for their own growth and energy needs. The final stage of biodegradation is the assimilation of the monomers into a microorganism to generate cellular biomass and carbon dioxide or methane depending on availability of oxygen (effectively air). Conditions with plenty of oxygen are described as aerobic, limited oxygen as anoxic and no oxygen as anaerobic). The rate of this stage can mostly be quantified by measuring gas evolution, or if a reaction is performed in a bioreactor, by increases in biomass of the chosen

microorganism. Some microorganisms (*e.g.* fungi) cannot metabolise plastics under anaerobic conditions, while other microorganisms require anaerobic conditions. Aside from oxygen, other environmental factors will affect both fragmentation and microbial degradation rate, such as pH, temperature, moisture content etc.

Impact of Biodegradable Plastic Mulch in Agricultural Soil Ecosystem



(Aoyun *et al.* 2023)

4.1 Impacts on soil Physicochemical Properties

There are growing concerns about the potential impacts of BDPs on physicochemical properties of agricultural soil. Physicochemical properties play a crucial role for maintaining soil function and are important indicators to evaluate soil health (Wang *et al.*, 2022d). Due to repeat and single-use applications of BDPs mulch, residual plastic debris and released additive chemicals would have negative impacts on soil environments as well as soil organisms habituated (Qi *et al.*, 2022). For instance, in the process of degradation, BDPs would release intermediates of organic carbon, which can increase organic carbon content of the soil. BDPs also could indirectly affect soil physicochemical properties through the cat ion of soil microbiota. Previous studies have demonstrated the alteration of soil pH via nitrobacteria, as well as changes of acid-base balance in the soil due to the adsorption of BDPs MPs (Feng *et al.*, 2022). Another study compared effects of plastic films between LDPE and starch-based BDPs of the same size and found both types of plastics had a great impact on soil structure including water infiltration, water retention and soil water repellency. In addition, BDPs mulch produced negative effects, but no significant changes in soil pH and electrical conductivity probably due to a relatively short incubation treatment term, *i.e.*, 1month (Qi *et al.*, 2020a). After

that, this research group conducted a four-month experiment and actually found that BDPs debris could significantly elevate soil pH, reduce electrical conductivity and change the C:N ratio of soil in a concentration-dependent manner. Similarly, other scholars also found that BDPs residuals increased soil bulk and the total N content, but reduced porosity, water holding capacity and C:N ratio of co-incubated soil (Koskei *et al.*, 2021). These studies indicate that application of BDPs in agricultural soil can markedly influence soil physicochemical properties.

4.2. Impacts on Crops

The consequence of BDPs on soil environments would further affect crop yield and other organisms and induce ecological risks. Several studies have shown toxic effects of BDPs debris and released additives on crops (Palsikowski *et al.*, 2018). Moreover, a greater impact of BDPs mulch was demonstrated on crops than non-biodegradable plastics (Qi *et al.*, 2018; Meng *et al.*, 2021). Among these studies, the majority of effect assessments were based on growth and development of crops. For instance, (Qi *et al.*, 2018) found that starch-based plastic mulch had significantly negative effects on growth of wheat and Micro Plastic (MPs) exhibited a greater negative impact on wheat crops in comparison to microplastics. (Yang and Gao 2022) found that BDPs MPs ultimately lead to the reduce of crop growth through inhibition of nitrogen metabolism and photosynthetic function in rice. In another study, effects of both BDPs MPs and LDPE MPs on the growth of navy beans were investigated and researchers found that BDPs significantly inhibited the biomass of roots and aboveground parts of navy beans, while PE MPs had significant effects on roots (Meng *et al.*, 2021). Obviously, there would be different impacts on crops between BDPs and conventional plastics, which might be related to the difference in their degradation and the fate of degradation products in soil environments.

4.3 Impacts on Soil Microbiome

The degradation of BDPs mulch in the soil is mainly carried out by certain species of soil microbiome. In turn, the degradation process can likely change the structure and quantity of microbial communities in surrounding soil. According to a recent study, BDPs had an impact on microbial abundance and related enzyme activity in soil (Serrano-Ruiz *et al.*, 2021), which would be due to the fact that the degradation of BDPs cause the release of monomers that were used by microorganisms as exogenous organic matters, resulting in an increase in microbial biomass. Moreover, mulch treatment of BDPs could induce change in water content and soil temperature, which would accelerate the growth and

development of plant roots thereby affecting microbial and enzyme activities (Li *et al.*, 2014; Barragan *et al.*, 2016). Another study disclosed an increase in the abundance of both bacteria and fungi in the soil after the mulch treatment of BDPs, but without significant effects on the enzyme profile within soil (Bandyopadhyay *et al.*, 2020), which suggests that the function of the soil microbial community was not significantly influenced by BDPs. However, according to (Qi *et al.* 2020b), the abundance of some specific bacterial genera (*e.g.*, *Bacillus*, *Omni bacterium* and *Clostridium*) in the inter-rhizosphere bacterial community were significantly increased after BDPs mulch fragments were buried in the soil for 4 months, but the abundance of other bacterial genera decreased, presenting different effects of size-different mulch fragments. Similarly, another study showed that burying treatment of BDPs mulch fragments for seven months caused an increase in the abundance of soil fungal and bacterial communities, especially the fungal plant pathogen *Setophoma terrestris* (Muroi *et al.*, 2016). In addition, Zhang *et al.* (2022) demonstrated that soil microbial activity, urease activity and peroxidase activity were significantly increased after BDPs mulching treatment in soil.

4.4. Impacts on Soil Fauna

Mesofauna have a high opportunity to ingest BDPs residuals in topsoil and induce adverse effects. Earthworms were usually considered as an important biological indicator for soil quality and ecological health (Zhang *et al.*, 2022). According to results of standard biotoxicological tests, earthworm's biomass and reproduction declined after exposure to PLA and PPC MPs of higher than 40 g/kg, which showed a relatively strong impact on earthworms in comparison to the same exposure of conventional MPs. If merely considering this result, the advantage of BDPs of environmentally friendly is somewhat doubtful. Similarly, Boots *et al.*, (2019) found that earthworm biomass decreased after soil exposure to BDPs in spite of no significant change in survival rates of animals. In addition, earthworms can in turn affect the degradation of BDPs in soil, as earthworms were proved to carry BDPs mulch fragments into deep soil layers, or take up and then excrete small plastic debris in composted soil condition, thus accelerate the degradation of BDPs.

Degradative Impact on Soil Ecosystem:

- ✓ **Microbial Activity:** The biodegradation process involves microorganisms breaking down BPM into simpler compounds. This can stimulate microbial activity in the soil, potentially benefiting nutrient cycling.

- ✓ **Nutrient Release:** As BPM breaks down, it can release nutrients stored within the mulch material, which may serve as a slow-release fertilizer for crops.
- ✓ **Soil Structure:** BPM can influence soil structure positively by enhancing water retention and aeration due to its biodegradation process.
- ✓ **Contaminant Concerns:** However, the degradation of some BPM materials can release chemical residues or additives, which might have unintended consequences on soil and groundwater quality.
- ✓ **Timeline:** The rate of biodegradation depends on several factors, including temperature, moisture levels and the specific BPM material used. Degradation may not be rapid and complete breakdown can take several months to years.

Effects of BDMs on Soil Microbial Communities

Studies have shown that BDMs can have both positive and negative effects on soil microbial communities. On the one hand, BDMs can provide a source of carbon and energy for soil microbes, which can lead to increased microbial activity and diversity. On the other hand, BDMs can also release substances that can inhibit microbial growth. The overall effect of BDMs on soil microbial communities is likely to depend on a variety of factors, such as the type of BDM, the environmental conditions and the composition of the soil microbial community.

Effects of BDMs on Soil Nutrient Cycling

BDMs can also have an impact on soil nutrient cycling. The breakdown of BDMs can release nutrients such as nitrogen and phosphorus into the soil, which can be beneficial for plant growth. However, BDMs can also release substances that can immobilize nutrients, making them unavailable to plants. The overall effect of BDMs on soil nutrient cycling is likely to depend on the same factors that affect their impact on soil microbial communities.

Degradation Factors

- ✓ **Environmental Conditions:** Soil temperature, moisture levels and microbial activity play pivotal roles in the degradation of BPM. Warmer and moister conditions generally promote faster breakdown.
- ✓ **Mulch Thickness:** Thicker mulch layers can take longer to degrade, as microbial access to the mulch surface is limited.
- ✓ **Microbial Communities:** The types and abundance of microorganisms in the soil influence BPM degradation rates. Some microbes specialize in breaking down biodegradable materials.

✓ **Soil Ecosystem Impact**

- ✓ **Carbon Enrichment:** BPM degradation contributes organic carbon to the soil, potentially improving soil organic matter content, water-holding capacity and nutrient retention.
- ✓ **pH Effects:** The breakdown of BPM can influence soil pH levels, which may impact nutrient availability and plant growth. Monitoring pH changes is crucial.
- ✓ **Nitrogen Release:** Some BPM materials release nitrogen during degradation, which can serve as a nutrient source for crops but should be managed to avoid excess nitrogen in the soil.
- ✓ **Residue Management:** Residues from partially degraded BPM can affect crop quality and soil structure. Proper residue management practices are essential.

Challenges and Considerations

- ✓ **Residue Management:** Farmers must address residue cleanup, as partially degraded mulch residues can interfere with planting and cultivation.
- ✓ **Material Selection:** The choice of BPM material is critical; some materials may leave behind residues or contaminants harmful to the soil.
- ✓ **Regulations:** Compliance with local regulations regarding BPM use and disposal is essential to avoid environmental issues.

Conclusion:

Biodegradable plastic mulch offers significant environmental benefits by reducing plastic pollution and potentially improving soil conditions. However, its impact on the soil ecosystem can vary depending on factors such as the material used and local environmental conditions. Farmers and researchers should carefully consider the choice of BPM and monitor its effects on soil health to ensure sustainable agricultural practices. Biodegradable plastic mulch presents a promising alternative to conventional plastic mulch for sustainable agriculture. Its impact on the soil ecosystem varies with factors like material type, environmental conditions and microbial activity. When used responsibly, BPM can improve soil health, reduce plastic waste and support sustainable farming practices. However, ongoing research and best management practices are necessary to optimize its benefits while minimizing potential drawbacks.

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PLANT DISEASES AND THEIR INTEGRATED MANAGEMENT

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Abstract:

Plant diseases significantly challenging global agriculture by impairing growth, development and productivity. They are broadly categorized into infectious diseases, caused by fungi, bacteria, viruses, nematodes, phytoplasmas and parasitic plants and non-infectious diseases, resulting from environmental stresses, nutrient imbalances, or chemical damage. These diseases manifest through a wide range of symptoms such as leaf spots, blights, galls, wilts, rots, chlorosis, stunting and tissue deformities, which are critical for accurate diagnosis. Historical outbreaks, including the Irish potato famine and coffee rust epidemics, demonstrate the profound economic and societal impacts of plant diseases. Effective management requires an integrated approach combining genetic host resistance, cultural practices, judicious chemical applications, biological control and regulatory measures. Early detection, preventive strategies and integrated disease management are essential for minimizing losses, maintaining sustainable crop production and ensuring food security. This chapter provides a comprehensive overview of bacterial, fungal and viral plant pathogens, their diagnostic symptoms and current strategies for integrated management, highlighting the importance of a holistic sustainable approach to protect crops, enhance productivity and promote sustainable agriculture.

Keywords: Bacterial Pathogens, Fungal Pathogens, Integrated Disease Management, Plant Diseases, Viral Pathogens.

Introduction:

Plant diseases are abnormal conditions in plants where normal physiological or structural functions are disrupted, leading to reduced growth, development and productivity. These diseases are broadly classified into two categories: infectious and non-

infectious. Infectious diseases are caused by living organisms, including fungi, oomycetes, bacteria, viruses, nematodes, phytoplasmas and higher parasitic plants and they can spread from plant to plant, sometimes resulting in widespread epidemics (Agrios, 2005). On the other hand, non-infectious diseases, also called physiological disorders, arise from environmental or chemical stresses such as nutrient deficiencies or toxicities, drought, waterlogging, temperature extremes and chemical damage. Although these disorders do not spread between plants, they can still severely reduce crop health and yield (Strange and Scott, 2005). Both types of plant diseases pose serious threats to agriculture, food security and the global economy, emphasizing the need for comprehensive management strategies.

The consequences of plant diseases on agriculture are of paramount importance. They lead to major yield losses, quality losses and contribute to economic challenges for farmers worldwide. Globally, plant diseases are estimated to cause annual economic losses exceeding 38 billion USD (Savary *et al.*, 2019). Beyond direct yield reductions, they impact food and nutritional security, decrease farm incomes and increase production costs due to the need for disease control measures. Historical events demonstrated the devastating potential of plant diseases, such as the Irish potato famine in the 1840s caused by *Phytophthora infestans* (Fry, 2020) and the 19th-century coffee rust epidemic (*Hemileia vastatrix*) in Sri Lanka, which transformed global coffee production (McCook, 2006). These examples demonstrate how plant diseases can affect not only agriculture but also societal and economic stability.

In India, where agriculture is central to the economy and provides employment to nearly half of the population, plant diseases pose significant challenges. Major crops like rice, wheat, maize, sugarcane, pulses, cotton and vegetables are frequently affected by serious diseases. Epidemics of rice blast (*Magnaporthe oryzae*), wheat rusts (*Puccinia* spp.), downy mildew in pearl millet, late blight of potato (*Phytophthora infestans*) and cotton wilt (*Fusarium oxysporum* f. sp. *vasinfectum*) have historically resulted in substantial yield losses in India (Ramakrishnan, 1963; Joshi and Nayak, 1984). The country's tropical and subtropical climate, combined with intensive cultivation practices, creates favorable conditions for the proliferation and persistence of pathogens. Therefore, studying plant diseases and implementing integrated management practices are essential for protecting farmer livelihoods and ensuring food security. With increasing population pressure, climate variability and agricultural intensification, adopting integrated disease

management strategies is now more important than ever. This chapter focuses on comprehensive overview of bacterial, fungal and viral plant pathogens, their diagnostic symptoms and current strategies for integrated management, highlighting the importance of a holistic approach to protect crops, enhance productivity and promote sustainable agriculture

Bacterial Diseases

Globally, over 5,000 bacterial species have been identified, of which more than 200 cause plant diseases, living as parasites within plant tissues, on surfaces, in debris, or in soil (Walsh, 2025). These bacteria, including *Erwinia*, *Pectobacterium*, *Ralstonia*, *Burkholderia*, *Xanthomonas*, *Clavibacter*, *Streptomyces* and *Phytoplasma*, cause galls, wilts, leaf spots, blights, soft rots, scabs and cankers and significantly limit crop productivity (Walsh, 2025; Singh and Kapoor, 2017). The first plant bacterial disease discovered was fire blight of pear and apple (*Erwinia amylovora*) by T. J. Burrill (Burrill, 1885). In India, epidemics of bacterial wilt (*Ralstonia pseudosolanacearum*), bacterial blight of rice (*Xanthomonas oryzae* pv. *oryzae*), citrus greening and pomegranate bacterial blight have caused severe yield losses (Singh and Kapoor, 2017; Singh, Pandey and Singh, 2016).

Diagnostic Symptoms of Bacterial Diseases

Bacterial infections in plants cause a variety of symptoms, including leaf spots, blights, wilts, cankers, galls, soft rots and scabs, which significantly affect growth and yield (Smith, 2025; Johnson, 2025). Leaf spots are often water-soaked, angular and bordered by veins, sometimes with bacterial ooze and are mainly caused by *Pseudomonas* and *Xanthomonas* (Johnson, 2025). Cankers appear as sunken lesions on stems, twigs, or branches, often exuding gum, commonly caused by *Pseudomonas* and *Xanthomonas* (Brown, 2025). Galls, caused primarily by *Agrobacterium* species, are overgrowths resulting from uncontrolled cell division at wounds (Davis, 2025). Vascular wilts occur when bacteria invade xylem vessels, causing wilting, yellowing and plant death (*Ralstonia*, *Xanthomonas*) (Brown, 2025). Soft rots involve tissue maceration and foul-smelling ooze, caused by *Erwinia*, *Pseudomonas* and *Bacillus* (Brown, 2025). Scabs, primarily caused by *Streptomyces*, produce rough, corky lesions on tubers (Davis, 2025). These diagnostic features help distinguish bacterial infections from other plant diseases (Williams, 2025).

Fungal Diseases

Fungi are major agents of plant diseases, causing significant preharvest and postharvest losses and affecting food security worldwide (Ellis, 2008; Agrios, 2020).

Historical outbreaks, such as bunt in wheat (*Tilletia* spp.), Irish potato blight (*Phytophthora infestans*), downy mildew in grapes (*Plasmopara viticola*) and stem rust in wheat (*Puccinia graminis tritici*), have caused devastating crop failures, famine and human migrations (Ellis, 2008; Singh and Kapoor, 2017). Fungal infections originate from contaminated seeds, soil, crop debris, weeds and nearby crops and spread via wind, water, contaminated tools, animals and human activity. Entry occurs through natural openings or wounds caused by pruning, harvesting, hail, insects, or other mechanical damage (Agrios, 2020). Common foliar pathogens include downy mildew, powdery mildew and white blister, while soilborne pathogens include *Clubroot*, *Pythium*, *Fusarium*, *Rhizoctonia*, *Sclerotinia* and *Sclerotium* spp., all of which cause symptoms like wilting, leaf spots, rots and galls (Ellis, 2008; Singh and Kapoor, 2017).

Diagnostic Symptoms of Fungal Diseases

Fungal diseases are among the most important causes of plant damage, affecting leaves, stems, roots, flowers and fruits and significantly reducing crop yield and quality (Ellis, 2008; Agrios, 2020). Downy mildew (*Plasmopara viticola*, *Peronospora* spp.) produces yellow or pale green spots on leaves with white downy growth on the underside, often causing leaf drop and shoot deformation (Ellis, 2008). Powdery mildew (*Erysiphe*, *Oidium*, *Sphaerotheca* spp.) appears as white powdery growth on leaves, stems and flowers, leading to chlorosis and necrosis (Agrios, 2020). White blister (*Albugo* spp.) forms white pustules on the undersides of leaves and deforms stems and flowers (Singh and Kapoor, 2017). Fusarium wilt (*Fusarium oxysporum*) causes yellowing, wilting, stunted growth and browning of vascular tissues (Ellis, 2008), while root rot (*Rhizoctonia solani*, *Pythium* spp.) leads to decayed roots, poor growth and damping-off in seedlings (Singh and Kapoor, 2017). Sclerotinia rot (*Sclerotinia sclerotiorum*) produces water-soaked lesions, white cottony mycelium and hard black sclerotia, resulting in plant collapse (Agrios, 2020). Clubroot (*Plasmodiophora brassicae*) causes swollen roots, wilting and nutrient deficiencies (Ellis, 2008). Leaf spot and blight (*Alternaria*, *Septoria*, *Colletotrichum* spp.) produce necrotic spots with concentric rings or chlorotic halos, often causing defoliation (Singh and Kapoor, 2017). Stem rust (*Puccinia graminis tritici*) produces reddish-brown pustules on stems and leaves (Agrios, 2020) and late blight (*Phytophthora infestans*) leads to water-soaked lesions, white fungal growth on leaves and tuber rot, historically causing famines (Ellis, 2008). These symptoms vary with pathogen, host and environmental conditions,

emphasizing the importance of accurate diagnosis for effective management (Singh and Kapoor, 2017).

Viral Diseases:

Plant viruses have caused significant agricultural losses worldwide, often leading to epidemics that affect major crops. Tobacco mosaic virus (TMV), first reported on tobacco, infects over 100 plant species, including vegetables and ornamentals, causing mosaic patterns, stunted growth and leaf distortion (Agrios, 2020; Singh and Kapoor, 2017). Cucumber mosaic virus (CMV) affects cucurbits, tomato and many other crops, leading to leaf curling, mottling, stunting and yield reduction; CMV outbreaks have been reported across Asia, Europe and North America (Walsh, 2025). Tomato yellow leaf curl virus (TYLCV) has devastated tomato production globally, particularly in India, the Middle East and Africa, causing leaf yellowing, curling, stunted growth and significant yield losses (Singh, Pandey and Singh, 2016). Potato virus Y (PVY) and Potato leafroll virus (PLRV) have been major constraints to potato production in Europe, North America and India, causing mosaic, necrosis and leaf rolling, reducing both tuber quality and yield (Agrios, 2020). Banana bunchy top virus (BBTV) is responsible for severe epidemics in banana plantations in Southeast Asia and the Pacific, leading to stunted, bunchy leaves and complete crop loss (Walsh, 2025). Viral epidemics are often facilitated by insect vectors such as aphids, whiteflies and leafhoppers, which transmit viruses systemically, making management challenging. Seed- and pollen-borne transmission, as well as human activities, further contribute to the spread of these pathogens (Singh and Kapoor, 2017). The widespread impact of viral diseases underscores the importance of resistant cultivars, vector control, cultural practices and strict quarantine measures to prevent epidemics (Agrios, 2020; Walsh, 2025).

Diagnostic Symptoms of Viral Diseases

Plant viruses induce a wide range of symptoms that affect growth, yield and quality. Mosaic refers to irregular intermingling of green and yellow patches on foliage, while mottle shows irregular patterns of light and dark areas (Agrios, 2020). Chlorosis is the abnormal yellowing of plant parts and vein clearing occurs when leaf veins turn pale or transparent. Stunting leads to reduced growth of the whole plant or plant parts, whereas distortion causes irregularly shaped leaves, stems, or fruits. Dieback is the progressive death of shoots, branches, or roots, often beginning at the tips. Leaf spots appear as lesions of varying color, shape and size, while ring spots display a dark outer ring with a lighter

center. Rugose symptoms result in wrinkled tissue and witches' broom produces abnormal, brush-like shoots. Decline refers to the gradual deterioration of overall plant health (Singh and Kapoor, 2017; Walsh, 2025). These characteristic symptoms help distinguish viral infections from bacterial or fungal diseases and are critical for early diagnosis and management.

Integrated Management of Plant Diseases

Plant diseases caused by bacteria, fungi and viruses are major constraints to global crop production, resulting in substantial preharvest and postharvest losses (Agrios, 2020; Singh and Kapoor, 2017; Walsh, 2025). Integrated Disease Management (IDM) provides a holistic approach by considering the production system as a whole, including soil health, pathogen biology, crop susceptibility, environmental conditions and human interventions. The primary goal is to prevent infections, reduce disease spread and maintain sustainable crop productivity rather than curing already infected plants. Successful management relies on combining multiple strategies genetic host resistance, cultural practices, chemical applications, biological control and regulatory measures tailored to specific pathogens and crops.

1. Genetic Host Resistance

Using genetically resistant cultivars, hybrids, or varieties is the most effective first line of defense against bacterial, fungal and viral pathogens. Resistant plants limit pathogen reproduction and disease progression, reducing dependence on chemical control. Examples include:

- **Bacterial Diseases:** Bacterial wilt-resistant solanaceous crops (*Ralstonia spp.*), bacterial blight-resistant rice (*Xanthomonas oryzae*).
- **Fungal Diseases:** Late blight-resistant potatoes (*Phytophthora infestans*), Fusarium-resistant tomatoes (*Fusarium oxysporum*), stem rust-resistant wheat (*Puccinia graminis*), downy mildew-resistant soybeans (*Peronospora manshurica*), apple scab-resistant apples (*Venturia inaequalis*).
- **Viral Diseases:** Mosaic virus-resistant cucurbits (*Cucumber mosaic virus*), tomato yellow leaf curl virus-resistant tomatoes (TYLCV), banana bunchy top virus-resistant banana cultivars (Singh and Kapoor, 2017; Walsh, 2025).

Additionally, systemic acquired resistance (SAR) can be induced using chemical elicitors to enhance plant immunity, providing broad-spectrum protection against multiple

pathogens (Janse, 2005). Breeding programs, including conventional and biotechnological approaches, are critical for developing resistant cultivars adapted to local environments.

2. Cultural Practices

Cultural methods are essential for minimizing pathogen buildup, spread and infection. Key practices include:

- Using disease-free, certified seeds or propagation materials.
- Crop rotation to disrupt pathogen life cycles.
- Proper irrigation management and maintaining balanced soil fertility to reduce plant stress.
- Timely planting and optimal spacing to prevent high humidity and dense foliage, which favor pathogen development.
- Removal of crop residues through burning or deep plowing to eliminate sources of inoculum.
- Soil pasteurization or solarization to reduce pathogen load in nursery and field soils.
- Minimizing mechanical injury during harvesting, pruning and handling to prevent entry points for pathogens.
- Proper postharvest storage conditions, including temperature and humidity control, to limit disease progression (Agrios, 2020; Janse, 2005).

3. Chemical Applications

Chemical control is an important component when preventive and cultural measures are insufficient. These include:

- **Bactericides:** Copper-based compounds, streptomycin and oxytetracycline for bacterial diseases.
- **Fungicides:** Pre-plant soil fumigants, seed treatments, foliar sprays and postharvest applications for controlling fungal pathogens. Preventive application is most effective, but some fungicides also have curative activity.
- **Antiviral Chemicals:** Limited, but treatments like plant defense inducers or systemic acquired resistance activators can help reduce viral disease severity.
- **Integrated Use:** Timing, proper dosage and targeting the active site of infection are critical for chemical efficacy and minimizing resistance development (Agrios, 2020; Janse, 2005).

4. Biological Control

Biological control uses beneficial microorganisms to suppress pathogenic activity. Examples include:

- **Fungi:** *Trichoderma harzianum* suppresses soilborne pathogens such as *Pythium*, *Rhizoctonia* and *Sclerotium* species.
- **Bacteria:** *Pseudomonas fluorescens*, *Bacillus subtilis*, *Burkholderia cepacia* and *Bacillus polymyxa* reduce fungal and bacterial disease severity in crops like cotton, rice, wheat, sugar beet and vegetables.
- Biological agents can compete for nutrients, produce antimicrobial compounds, induce plant defense responses, or parasitize pathogens, providing environmentally friendly disease management (Heydari *et al.*, 2000, 2004; Walsh, 2025).

5. Regulatory and Quarantine Measures

Preventing the introduction and spread of pathogens is critical, especially for viral and bacterial diseases:

- Strict quarantines to restrict movement of infected plant material, seeds and nursery stocks.
- Monitoring, inspections and certification programs to ensure pathogen-free propagation.
- Eradication of infected plants and prompt disposal to reduce inoculum sources.
- Enforcement of international phytosanitary regulations to prevent cross-border spread of epidemics (Singh and Kapoor, 2017).

Conclusion:

Bacterial, fungal and viral plant diseases continue to challenge global agriculture by reducing yield, quality and farmer livelihoods. These diseases manifest through a variety of symptoms, such as leaf spots, blights, wilts, cankers, galls, soft rots, scabs, mosaic patterns, stunting, chlorosis, leaf distortion, dieback and witches' broom, which help in early diagnosis and guide management strategies. Effective management relies on a comprehensive, integrated approach that combines resistant cultivars, sound cultural practices, judicious use of chemicals, biological control and strict regulatory measures. Early detection and preventive strategies are crucial for limiting pathogen spread and minimizing losses. Adoption of integrated disease management not only protects crops but also promotes sustainable agricultural practices, enhances food security and supports long-term productivity.

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HARNESSING TOMATO WASTE FOR SUSTAINABLE AND NUTRITIOUS MULTIGRAIN COOKIES

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Abstract:

The health crises like pandemics, chronic diseases and malnutrition and lack of affordable healthcare resources, poverty, pollution and water scarcity are rising as the major challenges to global human community. Because of that today's food industries are focussing on food security and health-oriented revolutions. Lycopene as a principal carotenoid found in tomatoes has laid the interest because of its antioxidant properties and health benefits in preventing the risk of heart diseases and cancer. Furthermore, tomato processing industry produces significant waste (skin, seeds, spoiled or rejected tomatoes) during processing. Though challenging to manage, this waste presents opportunity for reuse through value addition of food products while contributing sustainability and productivity.

Effective management of waste from tomato processing industry is a need of hour to reduce impacts on environmental ecosystem preventing damage to natural resources like soil and water. This chapter explores the potential of an innovative way to effectively manage an agricultural or food processing waste by utilizing lycopene rich tomato waste in enriching food formulations. Lycopene enriched food products prepared with tomato industry by-products offer a novel and sustainable approach to functional food development. In addition to cancer-preventing and heart health promoting properties of lycopene, tomato waste also provides dietary fiber, making it an ideal functional ingredient in food formulations like multigrain cookies. By combining the grains like wheat, oats and millet, the cookies gain a balanced nutritional profile, offering consumers a health-conscious snack alternative. The chapter also addresses the challenges in incorporating tomato waste to food formulations including the safety and quality, stability of lycopene, technical challenges, economic viability, scalability and research and development gaps

Keywords: Tomato Waste, Multigrain Cookies, Nutrition.

Introduction:

Nowadays, food is envisioned to reduce the risk against diseases linked to malnutrition, improve general health and wellbeing and provide the vital nutrients to humans in addition to satisfy hunger. Researchers and scientists are now focused on improvement in functional foods for the benefit of people on the basis of growing consumer awareness and advancements in technology that points to a significant relationship between diet and health. Food processing industry by-products are the prominent sources of bioactive ingredients and color pigments. Nutraceuticals, functional foods, food components, additives and cosmetics can all be made with these by-products. For the purposeful community, foods with functional ingredients are foods that provide nutritional benefits beyond basic sustenance. Conventional foods as well as supplemented, or enriched foods as well as dietary supplements are included in functional food category.

Products from bakeries are preferred segments of the food processing industry as they are easily fortified and improved to compensate a diversified dietary requirement. Because of its flavor, aroma and taste, cookies are the most often utilized bakery item by people of all ages. This is mostly because it is inexpensive, readily available in a variety of flavors, ready to eat and high in nutrients. Dry fruits, nuts, chocolate pieces, candies and other flavoring elements are also added either inside or on the surface of the cookies. Cookies provide significant amounts of essential nutrients and vitamins to our daily food demands. Many nutrition improvement programmes use cookies in many parts of the world particularly for low-income groups.

Today's cookies are evolving through the addition or subtraction of various ingredients. The use of whole grains derived composite flour made from wheat, oats, millets etc. enhances nutritional value of product. Multigrain flour due to its high fiber content, minerals and antioxidants, contribute to reduce the risk of noncommunicable diseases or lifestyle diseases like cancer, diabetes mellitus, obesity and heart disease. The nutritional advantages of grains including wheat, oats and millet are combined in multigrain cookies, which provide a flexible way to increase dietary fiber and micronutrient intake. Multigrain cookies, that collate the nutritional benefits of grains like wheat, oats and millet, offer a versatile platform for enhancing dietary fiber and micronutrient intake. Integrating tomato waste into multigrain cookies, not only delivers the health benefits of lycopene, but the food waste can also be curtailed, aligning with sustainable development goals. This chapter deals with utilization of tomato waste in

development of lycopene-rich multigrain cookies, offering a dual benefit of incorporating bioactive compounds while promoting sustainable practices.

Nutritional Status of Tomato Waste as A Source of Lycopene

Tomatoes and tomato products are recognized as the primary sources of lycopene molecule in the human diet (John and Marc, 2000). Even though it lacks provitamin A activity, lycopene has nearly twice the ability of β -carotene to quench singlet oxygen. Lycopene being effective antioxidant influences development and progression of receptor motion and cell cycle growth which is responsible for development of carcinogenic tumor (Heber and Lu, 2002). Tomato waste is primarily comprised of the peel and seeds and provides fibers as 25.2 – 50.6 % (Marcos *et al.*, 2006). Other components of tomato waste include 15.4–23.7 % protein, 5.4–20.5 % fat and 4.4–6.8 % mineral content. The chemical composition representing overall protein content, ash content, total fibers and moisture content in tomato waste as 8.80 %, 0.62 % 1.82 % and 93.9 % respectively (Suarez *et al.*, 2008). Tomato pomace is an industrial by-product, comprised of seeds, skin and a minor amount of flesh (Ariadne *et al.*, 2015). The study conducted on tomato pomace reported the main carotenoid components in tomato peel as lycopene, phytoene, phytofluene and beta-carotene (Effat *et al.*, 2014). In tomato processing unit around 5-10 % of overall mass is identified as waste. Approximately 16 % crude protein and 57 % fibers are found tomato pomace (Ariadne *et al.*, 2015) and has high concentrations of bioavailable substances that are used as food additives (Krzysztof *et al.*, 2019). Specialized metabolites, mainly polyphenolic substances such as flavanones and carotenoids like lycopene, are also present in significant amounts in tomato waste (Krzysztof *et al.*, 2019).

Health Benefits of Tomato and Tomato Pomace

Tomatoes possess antioxidant properties. Several recent pharmaceutical studies have revealed the importance of tomato fruit as a source of antioxidant compounds required for human metabolism. Phenolic acids are the main antioxidants in tomato pomace. They activate a defensive mechanism against oxidants as they are absorbed in the body (Serio *et al.* (2006). Daily intake of tomato base products has proven its linkage with lower possibility of breast cancer and prostate cancer (Story *et al.*, 2010). Tomato seeds are about 13% more rich in lysine as in case of soy protein (Majzoobi *et al.*, 2011). Moreover, no anti-nutritional factors have been discovered in tomato waste. Marques *et al.* (2015) analyzed the antioxidant properties and health benefits of tomato pomace. As per their study, increasing plasma lycopene levels can be linked to a lower risk of CVD and has been shown to improve CVD biomarkers. The main risk factor for CVD is bad cholesterol (LDL),

which is related to an increase possibility of cardiac disease. Tomato lycopene inhibits cholesterol synthesis and may improve LDL degradation, thereby preventing cardiovascular disease in humans (Ghadge *et al.*, 2019).

Utilization of Tomato Waste in Food Product Development

The utilization of dried ground form of tomato in tomato ketchup was assessed by Belovic *et al.* (2018). Dried ground form of tomato ketchup's nutrient content revealed an increase in dietary fiber and energy value (4.19 g/100 g and 3.74 kcal, respectively). Dried ground form of tomato ketchup is rich in total dietary fibers content than fresh tomato pomace ketchup because no seeds were removed during the manufacturing process. dried ground form of tomato ketchup contains significantly more protein than fresh tomato pomace ketchup. The effects of adding tomato powder (2 to 4 g per 100 g of flour), in wheat flour cookies were assessed (Bhat *et al.*, 2020). There was a notable improvement in the total phenolic content (0.52–0.71mg GAE/g) of tomato powder dough than control (0.38 mg GAE/g). The incorporation of tomato powder notable improved the antioxidant effects of cookies, like DPPH scavenging activity. The dried ground form of tomato was used in yoghurt fortified with fibers and antioxidant (Alqahtani *et al.*, 2020). Yogurt is low in fibers and antioxidants. The dried ground form of tomato was incorporated in proportion ranging from 0% to 2% to UHT milk. The addition of dried ground form of tomato increased the acidity and phenolic content. As a result of the addition of dried ground form of tomato, palatable yoghurt is successful product rich in dietary fibers.

Enhancing Value of Multigrain Cookies with Tomato Waste Lycopene

Mudassir and Hafiza (2015) prepared the cookies with dried ground form of tomato and studied their physicochemical properties. The nutritional characteristics of cookies containing variable quantities of tomato waste powder (0-25%) were studied. Cookies containing 20 and 25% tomato pomace powder had significantly higher crude protein and ash contents than the control and other treatments. The overall acceptability scores of the control and dried ground forms of tomato incorporated cookies were not significantly different, according to sensory analysis. Consumers reported their satisfaction for up to 5% replacement of wheat flour with tomato waste powder in cookies based on organoleptic properties.

The multigrain (wheat, finger millet, oats) cookies formulated by substituting wheat flour with tomato waste powder presents an appropriate way towards sustainability through functional food development. The cookies baked at 140-150 °C for 15-20 min (Pal *et al.*, 2018) in rotary baking oven contain 0.78-1.50 mg/100 gram of lycopene (Kadam and

Mane, 2022). The enhanced functional properties are associated with lycopene content in tomato pomace powder cookies. The total phenolic content as 0.82 -1.34 mg GAE/g and antioxidant activity as 21.88-40.95% represents functional efficacy tomato waste integrated multigrain cookies.

Challenges of Tomato Waste Incorporation

Incorporating waste from tomato processing into food products presents significant opportunities but also poses challenges in terms of safety and quality, consumer acceptance, technical challenges, economic viability, scalability and research and development gaps. It is challenging to maintain sensory quality of such tomato waste utilized food product. Tomato waste may impose unpleasant flavour and has fibrous texture that may affect the mouthfeel of multigrain cookies. Thus, standardized formulations in terms of sweeteners and fats are required to balance the overall flavour and texture profile of cookies. Ensuring the integrity of lycopene during baking process is equally important to justify its probable use in functional food formulations. High temperature during thermal processing can degrade lycopene affecting its antioxidant efficacy (Jatau *et al.*, 2017). However, multiple studies have revealed improved bioavailability of lycopene as a result of heat induced maceration enhancing lycopene release from tissue matrix (Unlu *et al.*, 2007; Honest *et al.*, 2011; Li *et al.*, 2023). Hence, monitoring the heat treatment during baking process with respect to time and temperature is crucial to minimize lycopene degradation while achieving desired bioavailability. Advanced techniques like encapsulation and post treatment addition have also been explored for retaining the lycopene quality (Li *et al.*, 2023). However, tomato processing waste is perishable that causes complications in its storage and transportation. Furthermore, advanced technologies required to extract lycopene from tomato waste are often costly. The diversity in waste quality from different industries affects consistency and reliability. Dealing with consumer mindset is a major challenge as they think waste derived products are substandard or unsafe without knowing its effectiveness. Hence, further research is required to attain the finest practices for integrating tomato waste to develop lycopene enriched products.

Sustainability and Economic Impact

Utilization of tomato waste in functional food development lowers the raw material cost. It aligns with sustainable development goals driven by food waste utilization and contribute to circular economy. The scaling of these technologies for utilizing tomato waste

as a safe and functional food ingredient in bakery or any food industry may incur extra cost. But this extra expenditure is often balanced by enhanced value of the food product.

Conclusion:

Functional food development by integrating lycopene rich tomato waste projects a sustainable approach and healthy innovation in value added food products cluster. Incorporating tomato waste into cookies provides an opportunity to offer healthy snack option to health cautious consumers while remarking effective waste utilization for sustainable approach. Imminent inventions to improve the sensorial and functional quality of cookies and similar products could address the consumer demand for healthy food while meeting sustainable goals.

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IMPACTS OF HORTICULTURAL ORGANIC FARMING WITH LIVESTOCK FARMING IN HILLY AREAS: ECOLOGICAL, ECONOMIC AND SOCIAL

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Abstract:

Integrated Farming Systems (IFS) that combine horticultural organic farming with livestock production offer a sustainable pathway to address ecological fragility, economic instability and social vulnerabilities in hilly areas. This paper explores the ecological, economic and social impacts of such integrated approaches within the framework of agricultural engineering. Drawing from global and regional research, it discusses how integration enhances soil fertility, bio-diversity conservation and carbon sequestration, while simultaneously diversifying farmer income, ensuring food security and empowering rural communities. Challenges such as limited infrastructure, market access and climate change vulnerabilities are critically assessed. The study concludes that integrated horticultural-livestock organic systems provide a holistic model for sustainable agricultural development in hilly terrains, balancing productivity with environmental stewardship and socio-economic resilience.

Keywords: Integrated Farming Systems, Horticulture, Livestock Farming, Organic Agriculture, Hilly Areas, Agricultural Engineering, Sustainability

1. Introduction:

Agricultural systems in hilly and mountainous regions face unique challenges compared to those in plains or fertile valleys. Steep slopes, fragile soils, erratic rainfall and limited mechanization options make these landscapes ecologically sensitive and economically vulnerable (Joshi, Tewari and Singh, 2020). Traditional farming practices in hilly regions have often revolved around subsistence-based mixed systems, where small-holder farmers combine crop cultivation, horticulture and livestock husbandry to meet household needs (Singh and Devi, 2019). However, increasing pressures from climate change, migration and unsustainable land-use practices have placed these fragile ecosystems at risk.

Integrated Farming Systems (IFS), particularly those combining horticultural organic farming with livestock management, have gained attention as viable strategies to promote resilience, sustainability and rural livelihood security (Kaur and Sharma, 2021). Agricultural engineering, with its focus on optimizing inputs, technologies and ecological processes, provides the framework for implementing these integrated approaches effectively.

This paper investigates the ecological, economic and social impacts of integrated horticulture-livestock organic farming in hilly areas. It argues that such systems offer both academic significance—by contributing to sustainable agricultural science—and applied benefits by addressing pressing livelihood and ecological concerns in hilly regions.

2. Integrated Approaches in Agricultural Engineering

2.1 Defining Integrated Farming Systems

Integrated farming systems involve the purposeful combination of different agricultural enterprises such as crops, horticulture, livestock, fisheries and agro-forestry in a mutually beneficial manner (Behera *et al.*, 2022). The objective is to maximize resource-use efficiency, recycle nutrients, diversify outputs and minimize risk exposure.

2.2 The Role of Agricultural Engineering

Agricultural engineering enhances integrated farming through:

- Soil and water management technologies (e.g., contour farming, terracing, irrigation efficiency).
- Livestock housing and waste management systems (e.g., biogas digesters, composting units).
- Post-harvest and value-addition technologies for horticultural products.
- Mechanization innovations adapted for hilly terrains (small tools, drones and eco-friendly machinery).

2.3 Organic Farming in Hills

Organic farming prohibits the use of synthetic inputs, relying instead on natural nutrient cycles, bio-fertilizers, compost and integrated pest management. In hilly regions, where chemical inputs often lead to soil degradation and water contamination, organic farming offers an ecologically compatible alternative (FAO, 2019).

2.4 Synergy Between Horticulture and Livestock

Horticulture provides fruits, vegetables and cash crops, while livestock contributes manure, traction and animal-based food products. Integrated organically, they form a

closed-loop system: crop residues feed animals and manure returns nutrients to soil, reducing dependency on external inputs (Rana *et al.*, 2022).

3. Ecological Impacts

3.1 Soil Fertility and Nutrient Recycling

Livestock manure is a rich source of organic matter and nutrients. When composted, it enhances soil microbial diversity and structure, improving water retention in slopes and reducing compaction in clay-rich hilly soils (Kaur and Sharma, 2021). Integrated systems foster nutrient cycling, reducing external fertilizer dependency by up to 60% (Sharma, 2020).

3.2 Erosion Control and Landscape Stability

Soil erosion is a critical threat in hilly terrains due to slope gradients and deforestation. Integrating perennial horticultural crops (e.g., apple, citrus, tea) with pastures stabilizes soils through root binding. Livestock manure increases soil aggregation; while mulching and agro-forestry practices reduce surface runoff (Joshi *et al.*, 2020).

3.3 Biodiversity Conservation

Horticultural-livestock systems support multiple species across trophic levels. Fruit orchards host pollinators and natural pest predators, while pastures provide habitats for micro-fauna. This biodiversity strengthens ecological resilience, aiding pest control and pollination services (Pretty *et al.*, 2018).

3.4 Water Management and Quality

Livestock waste, when treated via bio-digesters, prevents nitrate leaching and water contamination. Meanwhile, orchard root systems improve infiltration and groundwater recharge. Integrated systems enhance watershed management, crucial for hilly regions dependent on springs and streams (FAO, 2019).

3.5 Climate Change Mitigation

Agro-forestry-based horticultural systems act as carbon sinks. Combined with reduced synthetic fertilizer use, integrated organic farming reduces greenhouse gas emissions. For instance, integrated farms in Nepalese hills sequestered up to 3.5 Mg C ha⁻¹ annually (Pandey *et al.*, 2021).

4. Economic Impacts

4.1 Income Diversification

A key advantage of integration is risk-spreading. Farmers derive income from fruits, vegetables, dairy, meat, eggs and manure-based products such as compost or biogas (Rana

et al., 2022). This reduces vulnerability to market fluctuations or climatic shocks affecting a single enterprise.

4.2 Value Addition and Market Potential

Processing horticultural products (e.g., jams, juices, dried fruits) and livestock goods (e.g., cheese, ghee) enhances profitability. Organic certification allows access to niche markets and premium pricing. In Sikkim, integrated organic farms reported 25–40% higher profit margins compared to conventional systems (Sharma and Rai, 2019).

4.3 Employment Generation

Integrated systems create year-round jobs across cultivation, animal care, processing and marketing. This is particularly important in hilly regions with seasonal migration issues. Agro-processing units linked to horticultural products also provide non-farm employment (Behera *et al.*, 2022).

4.4 Risk Mitigation and Resilience

Diversified enterprises act as buffers. For example, if frost damages fruit crops, dairy or poultry can sustain income streams. Integrated systems thus improve household financial resilience against climatic uncertainties (Pretty *et al.*, 2018).

5. Social Impacts

5.1 Food and Nutritional Security

Integrated farms provide balanced diets, including fruits, vegetables, milk, eggs and meat. This addresses micro-nutrient deficiencies common in rural hill communities (FAO, 2019).

5.2 Preservation of Traditional Knowledge

Mixed farming practices in hilly regions have long relied on synergy between crops and animals. Modern organic-integrated systems validate and strengthen these indigenous methods, promoting cultural heritage alongside scientific advancement (Singh and Devi, 2019).

5.3 Gender and Youth Empowerment

Women play a central role in livestock care and horticultural processing. Income from integrated systems enhances women's decision-making power. Youth involvement in organic branding, agri-tourism and digital marketing reduces rural out-migration (Rana *et al.*, 2022).

5.4 Community Resilience and Cooperation

Integrated models encourage collective practices such as shared composting units, grazing areas and co-operative marketing. This strengthens social cohesion and bargaining power (Joshi *et al.*, 2020).

6. Challenges and Constraints

While integrated systems offer multiple benefits, their adoption faces challenges:

- *Land Fragmentation*: Small and scattered holdings in hills make integration complex.
- *Infrastructure Gaps*: Lack of storage, roads and processing units hinders profitability.
- *Knowledge Gaps*: Farmers need training in composting, organic pest management and value addition.
- *Market Barriers*: Certification costs and limited access to organic markets reduce benefits.
- *Climate Risks*: Landslides, erratic rainfall and frost threaten horticulture-livestock balance.

Addressing these requires supportive policies, extension services and community-based solutions.

7. Policy Implications and Recommendations

- *Agro-ecological Zoning*: Identify suitable horticulture-livestock combinations per micro-climate.
- *Capacity Building*: Train farmers in composting, bio-digester use and organic pest control.
- *Infrastructure Support*: Develop collection centers, cold chains and processing units.
- *Market Linkages*: Facilitate co-operatives, e-commerce and organic certification schemes.
- *Research-Extension Nexus*: Agricultural engineering institutions must collaborate with local communities for adaptive innovations.

Conclusion:

Integrated horticultural organic farming with livestock systems in hilly regions represents a sustainable agricultural engineering solution with significant ecological, economic and social benefits. By enhancing soil fertility, controlling erosion and conserving biodiversity, these systems restore fragile hill ecosystems. Economically, they diversify

income, reduce risks and open premium market opportunities. Socially, they improve nutrition, empower women, preserve traditional knowledge and strengthen community resilience.

Despite challenges, the holistic advantages make integrated approaches essential for long-term rural sustainability in hilly terrains. With supportive policies, farmer training and technological innovations, integrated farming can serve as a cornerstone for climate-resilient, profitable and socially inclusive agriculture in hill regions.

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COMPREHENSIVE OVERVIEW OF AGRICULTURAL SPRAYERS: TYPES, COMPONENTS, FUNCTIONS AND CALIBRATION

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Abstract:

Agricultural sprayers are pivotal in enhancing modern crop management by enabling precise and efficient application of agrochemicals, including herbicides, insecticides, fungicides, and foliar nutrients. This comprehensive overview explores the various types of sprayers high volume, low volume, and ultra-low volume (ULV) alongside their components, functions and calibration techniques. Key components such as pumps, tanks, agitators, air chambers, valves, pressure gauges, regulators, strainers, and nozzles play essential roles in the effective atomization and uniform distribution of spray materials. The choice of nozzle, including hollow cone, flat fan, solid stream, and flood jet, is critical to achieving desired spray patterns and coverage efficiency. Sprayers range from manually operated devices like knapsack and rocker sprayers to power sprayers and sophisticated mist blowers, catering to diverse crop types and field conditions. Accurate calibration using parameters such as nozzle discharge rate, swath width and operator speed ensures correct application rates, minimizing chemical wastage and environmental risks. Ultimately, understanding sprayer mechanics and proper operation is fundamental for sustainable, safe, and productive agricultural practices.

Keywords: Agriculture, Environmental, Nozzle, Sprayers, Sustainable

Introduction:

Agricultural sprayers are essential tools in modern crop management, enabling precise application of pesticides, herbicides, fungicides, fertilizers, and micronutrients to ensure optimal crop protection and nutrition. With the intensification of agriculture and

the growing need for sustainable practices, the role of sprayers has become increasingly significant in maximizing input efficiency while minimizing environmental impact. Sprayers help in delivering uniform droplet sizes, targeted application, and efficient coverage, thereby improving the effectiveness of chemical inputs and reducing wastage.

This comprehensive overview delves into the various types of sprayers from manually operated to sophisticated tractor-mounted and drone-based systems along with their key components, working functions, and the crucial process of calibration to achieve desired output accuracy. Understanding the design, operation, and maintenance of sprayers is vital for enhancing agricultural productivity, ensuring operator safety, and promoting sustainable farming practices.

A sprayer is a device used to spray a liquid, sprayers are commonly used for projection of water, weed killers, crop performance materials, pest maintenance chemicals, as well as manufacturing and production line ingredients.

- Sprayer is a machine to apply fluids in the form of fine droplets.
- Sprayers are mainly used for the following purposes:
 1. Application of herbicide, to destroy weeds.
 2. Application of insecticide, to control insect pests.
 3. Application of fungicide, to minimize fungus diseases.
 4. Application of nutrients required for the plant growth regulation directly to the plant foliage.

Functions of Sprayers:

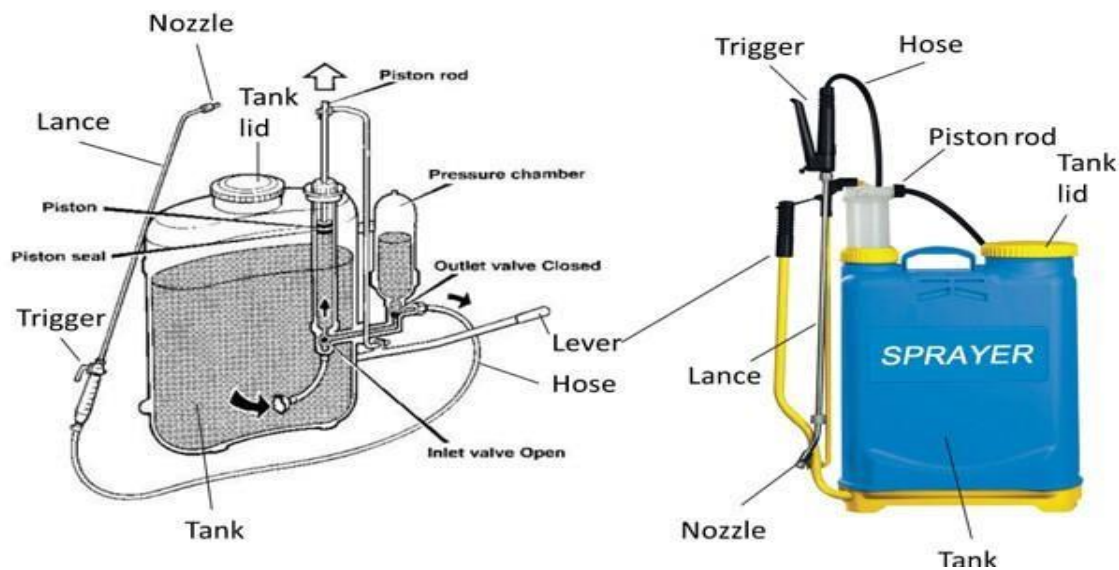
- Breaking the chemical solution in to fine droplets of effective size.
- Distributing the droplets uniformly over the plants.
- Applying the chemicals with sufficient pressure for positive reaching the plants
- Regulating the amount of liquid applied on plants to avoid excessive application

Desirable Quality of a Sprayer

A good sprayer should possess the following qualities

- It should produce a steady stream of spray material in desired droplet size so that the plants to be treated may be covered uniformly.
- It should deliver the liquid at sufficient pressure so that the spray solution reaches all the foliage and spreads uniformly over the plant body.
- It should be light in weight yet sufficiently strong, easily workable and repairable.

Basic Components of a Sprayer



Components of a sprayer are as follows a) Pump b) Chemical tank c) agitator d) Air chamber e) pressure gauge f) Pressure regulator g) valves h) Strainer i) suction line j) delivery line k) nozzles

Pump: A pump is a device used to move fluids, such as liquids or slurries, or gases from one place to another. A pump displaces a volume by physical or mechanical action. Most hydraulic sprayers are equipped with positive displacement pumps capable of developing pressure, required for many spraying jobs. The discharge capacity of these pumps is approximately proportional to the speed. A pressure relief valve or by-pass valve is required to protect these positive acting pumps from damage when the discharge line is closed and for the convenience of the operator.

Tank: It is the container to hold the chemical solution. It is made up of PVC, Brass, etc. It is usually made of metal sheet or synthetic rubber or plastic having good resistant quality against corrosion, erosion, and similar actions. The size of the tank varies according to the pump capacity and the requirements.

Agitator: It is the device which stirs the solution and keep the contents in homogenous condition. Positive agitation of spray material in the tank is essential to permit using the full range of spray materials including powdery emulsions, fungicides, cold water paints or other spray material. The propeller or paddle type mechanical agitators or hydraulic agitators are very common.

Air chamber: In a reciprocating type pump, an air chamber is provided on the discharge line of the pump to level out the pulsations of the pump and thus providing a constant nozzle pressure

Pressure gauge: It is a dial gauge which indicates the pressure at which the liquid is delivered from the pump. A pressure gauge properly calibrated, within the pressure range of the pump is provided on the discharge line to guide the operator for making proper adjustment of the pressure at site.

Pressure regulator: The pressure regulator serves several important functions. It is the means of adjusting the pressure as required for any spray job within the pressure range of the pump. With the positive displacement type of pump, it also serves as a safety device in automatically unloading the excess pressure by directing the unused discharge flow from pump back to the tank.

Valves: A valve is a device that regulates the flow of a fluid (gases, liquids, fluidized solids, or slurries) by opening, closing, or partially obstructing various passageways.

Cut-off valve is provided in the delivery line to control the flow from the pump,

By-pass valve is provided in the delivery line to by-pass the flow from pump to tank when flow in delivery line is reduced than the pump capacity

Relief valve - It is an automatic device to control the pressure of fluid or gas within a range a predetermined pressure.

Strainer: It is a small circular plastic ring with nylon wire mesh to filter any dust particle coming with the chemical solution It is included in the suction line between the chemical tank and the check valves. In some sprayers strainers are provided at the mouth of the chemical tank. Eg. Knapsack sprayers

Spray gun - It is a hand held metallic or PVC pipe to one end of which the nozzle is fitted and a flow cut off valve and a handle are fitted at the other end. The delivery hose is connected to the spray gun. It conducts the fluid from the delivery hose to the nozzle. The operator holds the gun and does the spraying job. Area of coverage by a spray gun is less compared to the coverage of a spray boom. Spray guns are used with low power sprayers E.g. Knapsack sprayers, rocker sprayer

Spray boom - It is a long metallic or PVC pipe to which several nozzles are fitted with. The delivery hose is connected to the spray gun. High power and high capacity sprayers use spray booms. The coverage is larger compared to spray guns. Booms are usually

mounted on suitable structures and used. E.g. Tractor operated sprayers, power tiller operated sprayers

Over-flow pipe - It is a conduit pipe through which excess fluid from a pump is bypassed in to chemical tank by the action of a relief valve or pressure regulator.

Nozzles: It is the component which breaks the fluid in to fine droplet. Automation of spray fluid is usually achieved by discharging the liquid through an orifice called nozzle under pressure.

Atomization is also achieved by breaking up the jet of liquid with a blast of air.

Nozzle Functions

- Atomizes liquid into droplets
- Provides hydraulic momentum
- Meters liquid at a certain flow rate
- Disperses the droplets in a specific pattern

Components of Nozzle

Nozzle body - It is the main component which encloses all other components of a nozzle

Swirl plate - It is metal disc with two tangential holes which imparts a swirl or rotation to the liquid passing through it

Nozzle disc - It is the component which breaks the fluid in to fine droplet. It is a flat disc with an orifice at the centre. When the spray solution reaches the disc from the swirl plate the disc builds up further pressure on the fluid and when the fluid passes out of the orifice, it breaks in to fine droplets.

The disc has a specific design to impart a hollow cone or solid cone or a flat fan type of discharge to the outgoing fluid.

The popular nozzles are a) hollow cone b) solid cone c) fan or flat type d) Flood jet Nozzle

Hollow Cone Nozzles

- These are used primarily where plant foliage penetration is essential for effective insect and disease control, and where drift is not a major consideration.
- At pressures of 40 – 80 psi hollow cone nozzles give excellent spray coverage to the undersides of reduces penetration correspondingly.

Flat Fan Nozzles

- These are used largely for broadcast spraying, where foliar penetration and coverage are not essential.

- The best operating pressure for flat fan nozzles is 15 – 30 psi, which produce coarser droplets that are not susceptible to drift

Flood Jet Nozzles

- These are ideal for high application rates and speeds, because they produce a wide-angle, flat fan pattern.
- Operating flood-jet nozzles at 5-25 psi minimizes drift, but pressure changes critically affect the width of the spray pattern.
- Generally, the spray generated by the floodjet is not as uniform as the flat-fan type.
- It is used for broadcasting fertilizers and post emergence herbicides

Solid Stream Nozzles

- The solid stream nozzle, also called a solid jet nozzle, is the simplest of all nozzles, being little more than a circular orifice at the end of a funnel.
- Solid stream nozzles give the highest impact of any spray pattern as the full momentum of the liquid is concentrated into a small area.
- Droplet size is irrelevant in solid stream nozzles as, unlike all other nozzles, the liquid is not atomised.



**Hollow cone
nozzles**

Flat fan nozzles

**Solid stream
nozzles**

Flood jet nozzle

Strainer- It is a small circular plastic ring with nylon wire mesh to filter any dust particle coming with the chemical solution

Spacer: There are two number of runner/ plastic rings placed in between nozzle plate and swirl plate and between swirl plate and strainer for effective travel of the solution

Nozzle Selection

Type of coverage	Nozzle type	Spray angle, (degree)	Discharge, cc/min	Operating pressure, Kg/cm ²
Foliage sprayin	Hollow cone nozzle	60	450	2.8
	Adjustable nozzle	75	450	2.8
Under leaf sprayin	Solid cone nozzle with back to back arrangement	70	450	2.8
shade trees	Adjustable nozzle	70	450	2.8
	Triple action nozzle	70	570	2.8
Weedicide spraying	Flooding nozzle	25 to 110	170 – 2100	0.7
Fertilizer spraying	Hollow cone nozzle	70 to 80	900 - 1200	2.8

Types of Sprayers

Based upon the volume of liquid handled, sprayers may be classified into

1. High volume sprayer (more than 400 litres /ha)
2. Low volume sprayer (5 to 400 litres/ hectare)
3. Ultra low volume sprayer (ULV) spray (less than 5 liters/ha).

1. High volume spray:

- ✓ All types of high volume sprayers have some kind of pump to supply pressurised spray liquid to the hydraulic nozzle which breaks the liquid into spray droplets and throws the spray away from it.
- ✓ The high volume sprayers are both manually operated or power operated type ➤ These are high capacity power operated hydraulic sprayers.
- ✓ They are the high volume spraying machines good for large scale application in orchards and tree crops.
- ✓ The source of power is engine or electrical motor.
- ✓ It consumes more time and labour.
- ✓ A pressure regulator is used to control the pressure in the discharge lines and by-pass from the pressure regulator is used for hydraulic agitation in spray tank

- ✓ High pressure like 400 psi can be built up and large spray discharge rate like 30 L/min.
- ✓ can be obtained (400 litres of spray/ha)
- ✓ The engine or electrical motors 3 - 5 HP capacity power the sprayer.

Types of High-Volume Sprayers

1. Hand Atomizer Type or Slide Pump

- These sprayers are provided with single-action or continuous action air compressor pumps. When the air is compressed, it is passed over the end of the suction tube which extends down into spray material.
- When the compressed sprayer escapes through the nozzle, it carries the spray material along with it. The blast of air breaks the spray material in the form of mist.
- A common type is a Misto-hand sprayer and flit gun. Such sprayers are commonly used for household purposes and kitchen gardens.

2. Stirrup Pump Type:

- This type of sprayer consists of a single or double acting pump which may be kept in a bucket or a barrel.
- A foot rest is also provided to hold the pump while working.
- Single acting pump delivers the spray material on the downward stroke only while the double acting pump ensures constant delivery of spray material. Such sprayers are commonly used for smaller fields.

3. Hand Compression Sprayer:

- It is a sprayer from which fluid is expelled by means of compressed air contained in a spray tank.
- This consists of an air pump fitted in an air-tight chamber.
- The chamber is filled with spraying liquid.
- The pressure is developed by pumping air into the tank and the spray is forced out under pressure.

4. Foot Type Sprayer:

- The pump of the sprayer is worked by operating a pedal lever by the foot of the operator.
- The spray liquid is kept in a bucket or container and it is sucked by a suction hose through a filter (strainer) due to piston movement. The liquid from the pump

cylinder is then delivered into a pressure chamber where from the pressurized liquid reaches the hydraulic nozzle.

- The foot operated sprayer is basically for orchard and tree spraying. Hydraulic pressure of 10 kg/cm² can be achieved which is necessary to project the jet of spray to tall trees simultaneously from two spray nozzles.

5. Rocker sprayer:

- It is a hand-operated sprayer that is used for spraying low crops and tall trees, go-downs and factories.
- It develops high pressure.

6. Knapsack sprayer:

- It is sprayer with the fluid container carried on the back of the operator.
- It is a compressed air type sprayer which has an air tight chamber. An air pump is mounted on the chamber.
- The container is filled 3/4th full so as to leave the enough space to compress a good volume of air above the spray material.
- A few strokes of the pump build-up enough pressure in the air chamber.
- When the nozzle is opened, the spray material is forced out through nozzle by the compressed air.
- These sprayers are suited for small area only.

Types of the Knapsack Sprayer

1. Knapsack Manual Sprayer
2. Knapsack Electric Sprayer
3. Knapsack Power Sprayer

Knapsack Manual Sprayer

- By its name, we can see that this type works manually by the hand movements mechanism to obtain a certain level of gas pressure.
- The tank is made of plastic and comes in multi size capacity, start from 4 until 9 litre. But for a medium size agriculture business, farmers use the stainless steel tank with a
- capacity in 14 litre. To maintain time efficiency spraying process rather than doing multi times of composite preparation.

Knapsack Electric Sprayer

- This sprayer using electric pump mechanism. Tank capacity available in 5 until 8 litre, for bigger size in 16 litre.
- Knapsack electric sprayer nowadays is widely chosen by farmers because of it works not by hand pumping mechanism. By doing so farmers can focus more on pest and disease control on the plants.

Knapsack Power Sprayer

- Many farmer preference of sprayer.
- Pump energy derives from a machine of high pressure motor up to 8 litre per minute.
- The machine itself requires fuel, it can be in pure gasoline or you can use a mixed of oil and gasoline in the ratio of 1:25.



**Knapsack Manual
Sprayer**



**Knapsack Electric
Sprayer**



Knapsack Power Sprayer

2. Low Volume Spray:

- It is between 50-150 litres/hectare.
- It uses an air stream from the fan as a herbicide carrier with small quantities of liquid. It is a precise applicator, hence saving material as well as labour.
- Motorised knapsack sprayer, also called Mist blower is a low volume sprayer in which gaseous energy nozzle is used for fine breakup of spray liquid. This type of nozzle is also called Air blast nozzle
- The force of escaping air at high velocity is utilised to shear down the spray liquid into fine spray droplets

The size of spray droplets depends upon:

1. Air velocity and volume
2. Liquid flow rate

3. Properties of Spray Liquid

- The spray droplets are then blown away from the nozzle outlet. The blast of air disperses the droplets over wide area and helps penetration of spray into the crop canopy.
- A two-stroke petrol engine (35 cc capacity) is used as prime mover to run a fan blower.
- The engine runs usually at 5000 - 6000 rpm and the blower emits at nozzle outlet about 5 m³ air per minute and at about 170 km/hr velocity.
- The spray droplets are about 150 – 220-micron Volume Median Droplets (VMD) size
- The flow rate up to 2 L/min can be obtained.

3. Ultra-Low Volume Spray (ULV):

- It is less than 5 litres/hectare.
- This spraying can be defined as plant protection operation in which total volume of liquid applied amount to a few milli-litre per acre.
- It is mainly used in air-craft spraying. The sprayer has a motor powered by 6-12 V battery. To the motor is attached a spinning disc, having grooves or teeth, and rotates at a very high revolution per minute (4000-9000). The spinning disc receives the concentrated chemical from a plastic container having a capacity of 1 litre approximately.
- Average droplet size varies from 35-100 micron.
- It is used for application of weedicide and for spraying small trees and crops.



Ultra-low volume sprayer used for herbicide application

Power Sprayers

- All the sprayers which impart the mechanical energy developed by an I.C. Engine, on the spray fluid before spraying is called as a power sprayer.

- The most commonly used type of power sprayer in India is a gaseous energy type knapsack sprayer.
- In construction, it has a back pack stand on which a blower with a S.I.
- Engine of 1.2 to 3 hp capacity, the spray fluid tank and the petrol tank are fixed rigidly.
- A pleated hose is attached to the blower elbow to carry the high velocity air and at the end of that a shear nozzle is fixed to allow the spray fluid to trickle in from the spray fluid storage tank, with a valve control.
- From the top of the blower casing, an air hose is taken into the spray fluid tank, which carries little quantum of air to press the spray fluid during operation.
- In operation, the engine is started by keeping the unit on the ground and then carried by the operator.
- The blower sucks the air behind the backrest and forces it into the pleated hose.
- The valve of the shear nozzle is opened or the shear nozzle with selective opening and discharged through the nozzle.
- The high velocity air shears off the droplets and atomizes by the impact of diffuse and delivers it on the plant the surface.
- An air current of 2.7 to 9.1 m² / minute is delivered at a velocity of 175 to 320 kmph.
- The spray fluid tank capacity varies from 7 to 12 litres.
- The fuel tank capacity varies from 0.75 to 2.25 litres.
- The spray fluid discharge can be varied from 0.5 to 5 lit / minute.

A power sprayer can be used as a power duster by making the following changes.

Chemical filler cap is removed to dismantle that strainer with the air pipe.

- The liquid delivery pipe below the chemical tank is dismantled and removed with the shear nozzle.
- The tank is thoroughly cleaned to remove possible traces of moisture left inside.
- The dust agitator tube is fixed at the bottom of the chemical tank.
- This tube has holes at the bottom to prevent the entry of dust into the agitator and clogging it.
- Dust intake tube is inserted into the chemical tank at the discharge and this tube has no.
- of large size holes on its periphery.

- Dust intake tube and the blower elbow are connected by using the dust outlet pipe, which is a pleated hose.

Calibration of Sprayer

- The rate of application of herbicide should be uniform over the whole of the field area.
- Too much application as well as too less application of pesticide dose is both undesirable
- Too much application- Wastage, crop injury, uneconomical
- Too less application -Poor weed control, wastage of herbicides, time and money
- The calibration of the sprayer, therefore, is essential to make sure that the pesticide is applied correctly and evenly. The sprayer should be checked and calibrated frequently
- The pesticide distribution by any sprayer is regulated by
 1. Nozzle spray discharge rate
 2. Swath width
 3. Walking speed of operator
 4. There are many methods described for calibration of the sprayer. Avery's simple and easy to remember formula is

$$F = SDA / 10000$$

Where **F** – flow rate in L/min

(This represents the flow rate from all the nozzles of the sprayer if they are more than one. But if there is only one nozzle, then the flow rate from one nozzle only)

S- Swath width in meter

D- Operator's walking speed in m/min

A- Application rate in L/ha

The above formula is useful for the calibration of any type of field spraying system i.e. high volume, low volume, ultra-low volume, tractor mounted sprayer or aerial spraying

Conclusion:

Sprayers are indispensable tools in modern agriculture, playing a critical role in the precise and efficient application of agrochemicals such as herbicides, insecticides, fungicides, and foliar nutrients. Their effectiveness depends on proper selection, maintenance, and calibration, ensuring uniform application, minimizing wastage, and

enhancing crop protection and productivity. The wide variety of sprayers ranging from high-volume to ultra-low-volume types caters to diverse crop needs and field conditions. Components such as pumps, nozzles, pressure regulators, and spray guns/booms work in unison to atomize and deliver the spray solution effectively. Nozzles, being the heart of the spraying system, must be selected based on the intended use and required spray pattern to ensure optimum coverage. Power sprayers, mist blowers, and motorized knapsack sprayers further enhance efficiency and reduce labor dependency. Accurate calibration is crucial to achieve the desired application rate, avoid overuse or underuse of chemicals, and ensure environmental safety. In conclusion, understanding the structure, function, and operation of sprayers is vital for sustainable and productive crop management, especially in the context of increasing demands on agricultural efficiency and environmental stewardship.

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NANO PESTICIDES AND NANO HERBICIDES: CONTROLLED RELEASE AND ENHANCED EFFICIENCY

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Abstract:

Nano-pesticides and nano-herbicides represent a next-generation approach to sustainable crop protection, addressing the limitations of conventional agrochemicals, such as low bioavailability, rapid degradation, and environmental contamination. By leveraging nanotechnology, active ingredients can be delivered through nanoscale carriers such as polymeric nanoparticles, nanocapsules, nanoemulsions, and mesoporous silica nanoparticles enabling controlled and stimuli-responsive release. These systems enhance absorption, bioavailability, and stability, allowing for reduced dosages while maintaining or improving efficacy against pests and weeds. Recent research demonstrates that nano-agrochemicals can improve target specificity, minimize off-target effects, and lower environmental impact. Despite their promise, challenges remain, including potential toxicity, regulatory gaps, production costs, and public perception. Integrating nanotechnology with precision agriculture and sustainable synthesis methods offers a pathway to safer, more efficient, and environmentally responsible crop protection. This chapter highlights the principles, applications, mechanisms, and future prospects of nano-pesticides and nano-herbicides, emphasizing their potential contribution to global food security and the advancement of sustainable agricultural practices.

Keywords: Nano Pesticides, Nano Herbicide, Nano Carriers

Introduction:

Overview of traditional Agrochemicals

Traditional pesticides and herbicides have been instrumental in maximizing agricultural output, yet their widespread and often indiscriminate application poses significant environmental and health concerns (Ali *et al.*, 2023; Yadav *et al.*, 2021). Key limitations include rapid degradation, off-target movement, development of pest

resistance, and low bioavailability, resulting in a substantial portion of active ingredients failing to reach their intended targets (Camara *et al.*, 2019). This inefficiency necessitates higher application rates, exacerbating issues such as soil and water contamination, harm to non-target organisms, and potential risks to human health (Ali *et al.*, 2023; Chaud *et al.*, 2021; Yousef *et al.*, 2023). The global market for conventional pesticides and herbicides, projected to reach USD 82.9 billion by 2027, underscores the urgent need for sustainable alternatives (Ali *et al.*, 2023).

Emergence of Nanotechnology in Agriculture

Nanotechnology, operating at the nanoscale (1–100 nm), presents a transformative approach to addressing the inherent challenges of conventional agrochemicals (Kumar *et al.*, 2018). By enabling the precise manipulation of materials at this dimension, nanotechnology offers unique physicochemical properties, such as a high surface area-to-volume ratio, that can be harnessed for agricultural innovation (Yadav *et al.*, 2021). Agri-nanotechnology, an emerging discipline, provides diverse nanomaterials for improved agricultural management, including nano-pesticides, nano-herbicides, and nano-fertilizers (Tripathi *et al.*, 2023). This field promises to enhance resource use efficiency and facilitate targeted applications, thereby reducing crop losses and environmental impacts.

Scope and Importance of Nano Pesticides and Nano Herbicides

Nano-pesticides and nano-herbicides represent a new generation of agrochemicals designed to deliver active ingredients more efficiently and sustainably (Ali *et al.*, 2023; Yin *et al.*, 2023). Their primary objectives include achieving controlled release and enhancing efficacy, which collectively contribute to reduced chemical input, minimized environmental footprint, and improved crop protection (Camara *et al.*, 2019; Tripathi *et al.*, 2023). Smart nano-based pesticides aim to deliver active ingredients in response to biotic and abiotic stressors through targeted and controlled release mechanisms (Camara *et al.*, 2019). This chapter will comprehensively examine the principles, applications, challenges, and future prospects of these advanced formulations in fostering sustainable agriculture.

Literature Review

The efficacy of nano-agrochemicals stems from the unique principles of nanotechnology. At the nanoscale, materials exhibit altered physical, chemical, and biological properties compared to their bulk counterparts (Kumar *et al.*, 2018). The significantly increased surface area-to-volume ratio of nanoparticles enhances their reactivity, solubility, and penetration capabilities (Yadav *et al.*, 2021). These properties

improve absorption by plants, enhance spreading on pest surfaces, and strengthen interactions with biological targets, resulting in greater effectiveness even at lower concentrations (Yin *et al.*, 2023).

Nano Carrier Systems for Controlled Release

Controlled release is a cornerstone of nano-agrochemical development, aiming to deliver active ingredients precisely when and where needed, over extended periods (Kumar *et al.*, 2021; Lee *et al.*, 2022). Various nano-carrier systems have been developed:

- **Polymeric Nanoparticles:** Encapsulate active ingredients within a polymer matrix, enabling sustained release. Their small size facilitates soil diffusion, and surface modifications allow specific targeting (Lee *et al.*, 2022). These are widely used in nano-herbicide formulations (Abigail & Chidambaram, 2017; Jalil & Ansari, 2020).
- **Nanocapsules:** Vesicular systems with a polymer shell enclosing an active ingredient. They can be designed for stimuli-responsive release, such as pH-sensitive properties, enhancing retention and utilization on crop leaves (Chen *et al.*, 2020).
- **Nanoemulsions:** Thermodynamically stable oil–water mixtures stabilized by surfactants, providing high encapsulation efficiency and enhanced penetration (Yadav *et al.*, 2021).
- **Mesoporous Silica Nanoparticles (MSNs):** Offer high loading capacity and controlled release due to their porous structure and can be surface-modified for pesticide delivery (Plohl *et al.*, 2020).
- **Stimuli-Responsive Systems:** Smart nano-pesticides that release active ingredients in response to environmental triggers such as pH, temperature, or light (Camara *et al.*, 2019; Huang *et al.*, 2018). For example, nanocomposite-based temperature-responsive herbicide particles have been developed (Chi *et al.*, 2017).

These systems provide clear advantages over conventional methods by reducing environmental pollution, improving efficiency, and ensuring targeted delivery (Kumar *et al.*, 2021). Tables 1 and 2 provide a comparative overview of conventional versus nano-agrochemicals and summarize different nano-carrier systems with their specific agricultural applications, highlighting improvements in efficiency, targeted delivery, and environmental sustainability."

Table 1: Comparison between conventional and Nano agrochemicals

Parameter	Conventional Pesticides/Herbicides	Nano-Pesticides/Nano-Herbicides
Solubility	Often poor for hydrophobic compounds	Improved solubility via nano-carriers
Stability	Rapid degradation (UV, hydrolysis)	Enhanced stability and protection
Release	Immediate, uncontrolled	Controlled, sustained, or stimuli-responsive
Targeting	Non-specific, off-target effects	Functionalized for site-specific delivery
Application Rate	High, repeated doses required	Lower doses, fewer applications
Environmental Impact	High contamination risk	Reduced leaching and runoff

Table 2: Types of Nano carriers and their agricultural application

Nano-Carrier Type	Structural Features	Agrochemical Application	Example References
Polymeric Nanoparticles	Biodegradable polymer matrices	Sustained release of pesticides	Lee <i>et al.</i> , 2022
Nanocapsules	Polymeric shell with liquid core	pH/light-responsive pesticide release	Chen <i>et al.</i> , 2020
Nanoemulsions	Oil-water colloidal systems	Solubilizing hydrophobic pesticides	Yadav <i>et al.</i> , 2021
Mesoporous Nanoparticles (MSNs)	Silica High surface area, porous structure	High-capacity loading, herbicide delivery	Plohl <i>et al.</i> , 2020
Metallic Nanoparticles (Ag, ZnO, CuO)	Antimicrobial/biocidal activity	Dual role: nutrient + pest control	Kumar <i>et al.</i> , 2018

Mechanisms of Enhanced Efficacy

Nano-agrochemicals enhance efficacy through multiple mechanisms:

- **Improved Absorption and Translocation:** Small particle size allows greater uptake and systemic movement within plants (Yin *et al.*, 2023).

- **Enhanced Bioavailability:** Nanoparticles increase the solubility of poorly soluble active ingredients, improving their action on target organisms (Plohl *et al.*, 2020). For instance, nanosuspensions show superior dispersibility and foliar wetting/retention, enhancing bioavailability (Ding *et al.*, 2024).
- **Protection from Degradation:** Nano-carriers shield active ingredients from premature degradation by UV light, hydrolysis, or microbial action (Chen *et al.*, 2020).
- **Precise Targeting:** Surface modifications and intelligent release mechanisms enable active ingredients to act specifically on pests or weeds, reducing off-target effects and minimizing dosage requirements (Camara *et al.*, 2019).

Current Status of Nano Pesticides and Nano Herbicides Research

Recent research emphasizes developing formulations that require lower amounts of active ingredients but demonstrate higher efficiency (Yadav *et al.*, 2021). Nano-agrochemicals show potential to increase crop yields while reducing environmental contamination (Ali *et al.*, 2023). Multifunctional nanoparticles with improved absorption, reduced dosage, and delayed resistance are gaining attention (Yin *et al.*, 2023). Current studies explore nanoemulsions, nanosuspensions, and nanogels for diverse applications (Yadav *et al.*, 2021).

Nano-herbicides are emerging as innovative strategies to address limitations of conventional herbicides, especially in annual weed management (Abigail & Chidambaram, 2017). These formulations, often based on polymeric or metallic nanoparticles, rely on controlled release mechanisms to enhance efficiency (Jalil & Ansari, 2020). By lowering herbicide consumption while improving productivity, they minimize crop and environmental damage (Abigail & Chidambaram, 2017). Smart herbicides with environmentally responsive release, such as temperature-sensitive nanocomposites, are under active development (Chi *et al.*, 2017).

Applications in Agriculture

Controlled Release of Active Ingredients

Controlled release formulations of nano-pesticides and nano-herbicides are designed to release active ingredients gradually, maintaining effective concentrations for longer durations (Kumar *et al.*, 2021). This reduces the frequency of application, prevents sudden toxicity spikes, and improves field-level efficiency. For example, polymer-based nanoparticles have been employed for the sustained release of herbicides, resulting in

prolonged weed control (Abigail & Chidambaram, 2017). Similarly, nanoencapsulation of pesticides ensures protection from environmental degradation and targeted delivery to pests (Chen *et al.*, 2020).

Target Delivery to Pest and Weeds

Nanocarriers can be surface-functionalized to enhance selectivity, ensuring delivery specifically to pest organisms or weed tissues. This precision reduces collateral damage to beneficial organisms and minimizes herbicide injury to crops (Camara *et al.*, 2019). For instance, ligand-functionalized nanoparticles can identify and bind to pest-specific receptors, releasing active ingredients at the exact site of infestation (Huang *et al.*, 2018). In weed management, nano-formulations improve foliar uptake and translocation within weed tissues, enhancing herbicide efficacy (Jalil & Ansari, 2020).

Improvement in Crop Yield and Quantity

By improving the bioavailability of agrochemicals and reducing losses due to volatilization or leaching, nanotechnology can enhance crop yields and quality (Ali *et al.*, 2023). Studies indicate that nano-formulated insecticides and herbicides contribute to higher pest mortality rates, better weed control, and ultimately increased agricultural productivity (Yin *et al.*, 2023). Additionally, the reduced use of active ingredients lowers the risk of crop residue accumulation, aligning with food safety standards (Camara *et al.*, 2019).

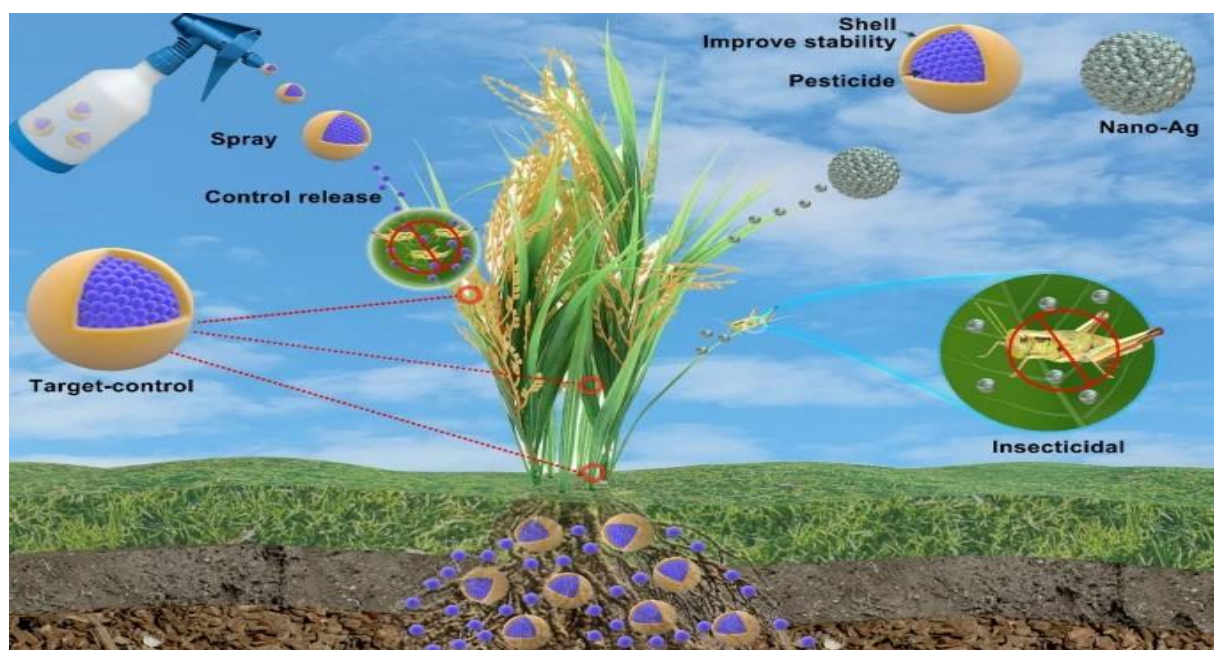


Figure 1: Role of Nanomaterials in Enhancing Pesticide Stability, Controlled Release, and Soil Retention (An *et al.*, 2022)

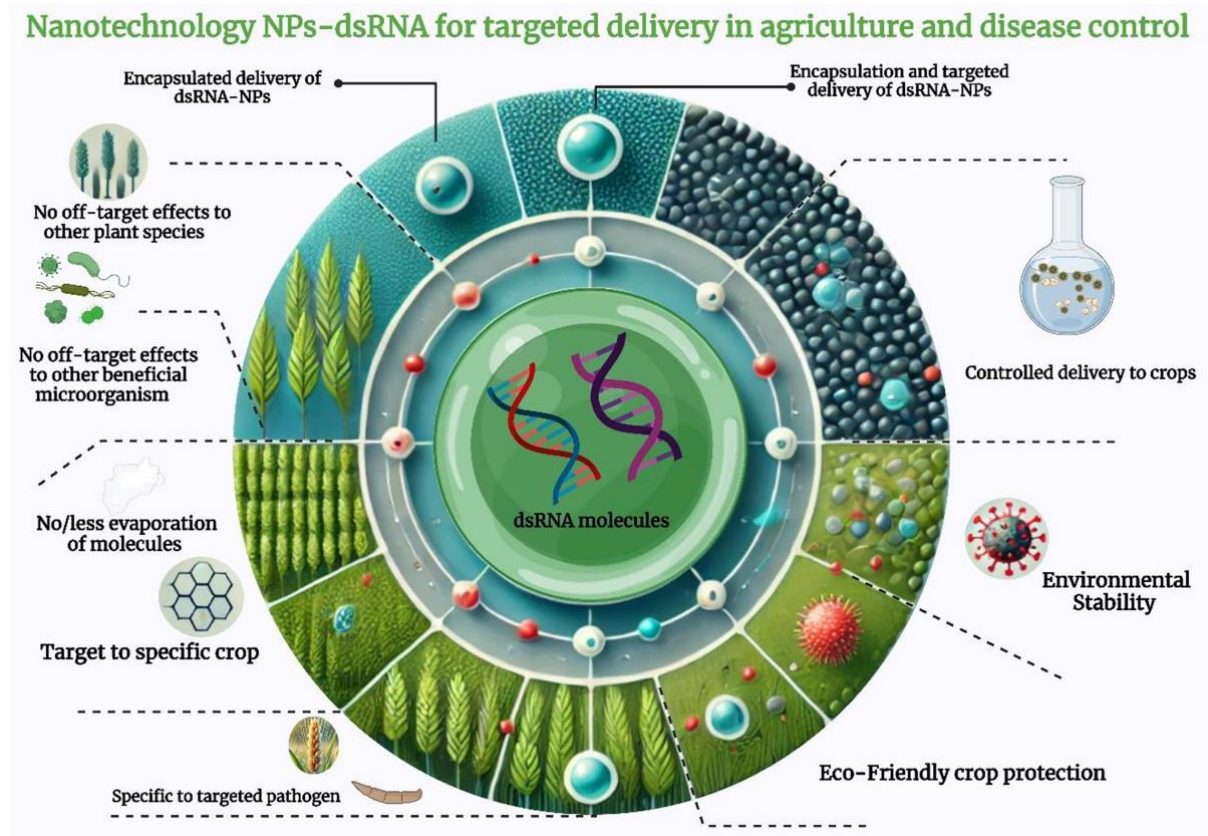


Figure 2: Nanotechnology: targeted delivery in agriculture and disease control
(Imran *et al.*, 2025).

Environmental Benefits

One of the most important advantages of nano-pesticides and nano-herbicides is their potential to mitigate environmental impacts. Controlled release reduces excessive chemical runoff into soil and water systems (Plohl *et al.*, 2020). Encapsulation techniques protect non-target organisms and decrease the risk of bioaccumulation (Chen *et al.*, 2020). Furthermore, reduced application rates and targeted delivery contribute to decreased pesticide residues in food and agricultural ecosystems, addressing key consumer and regulatory concerns (Ali *et al.*, 2023).

Challenges and Limitations

Environmental and Health Concerns

Despite their advantages, nano-pesticides and nano-herbicides raise concerns regarding long-term environmental and health impacts. Nanoparticles may persist in soil or water, potentially altering microbial communities, entering food chains, and affecting non-target organisms (Chhipa, 2022; Tripathi *et al.*, 2023). Their small size increases the likelihood of uptake by unintended species, raising bioaccumulation risks. Recent studies

also highlight the limited understanding of nanoparticle transformation, degradation, and toxicity under real field conditions (Sasson *et al.*, 2022; Yin *et al.*, 2023).

Regulatory and Safety Issues

The regulatory frameworks for nano-agrochemicals are still underdeveloped. Most pesticide regulations are designed for conventional formulations and do not adequately address nanoscale properties (Ali *et al.*, 2023). Challenges include defining safety thresholds, evaluating nanoparticle-specific toxicological effects, and standardizing risk assessment protocols (Chhipa, 2022). Regulatory uncertainty delays commercialization and adoption, particularly in regions with strict environmental legislation (Sasson *et al.*, 2022).

Technical Limitations and Field Level Applications

Although nano-agrochemicals show great promise in laboratory and greenhouse studies, large-scale field applications remain limited. Challenges include scalability of production, stability during storage, and cost-effectiveness compared to conventional pesticides (Plohl *et al.*, 2020; Camara *et al.*, 2019). Field heterogeneity—such as variations in soil pH, moisture, and organic matter—can influence nanoparticle behavior and limit uniform efficacy (Lee *et al.*, 2022; Huang *et al.*, 2018).

Knowledge Gap

There remains limited awareness among farmers, policymakers, and consumers regarding nano-agrochemicals. Public skepticism about nanotechnology, particularly concerning food safety and human health, may slow adoption (Yin *et al.*, 2023). Furthermore, interdisciplinary research integrating nanotechnology, agronomy, and toxicology is still insufficient, restricting the development of safe and commercially viable nano-formulations (Tripathi *et al.*, 2023).

Future Perspective and Conclusion

The future of nano-pesticides and nano-herbicides lies in developing smart, eco-friendly, and cost-effective formulations that integrate seamlessly with sustainable agriculture and precision farming systems. Key research directions include:

- **Stimuli-Responsive Nano-formulations:** Designing nanoparticles that respond to environmental triggers (e.g., pH, enzymes, temperature, or pest attack) for on-demand release of active ingredients (Camara *et al.*, 2019; Huang *et al.*, 2018).

- **Biodegradable and Green Nanomaterials:** Replacing synthetic carriers with biodegradable polymers, plant-based nanomaterials, and bio-inspired designs to reduce ecological risks (Tripathi *et al.*, 2023; Sasson *et al.*, 2022).
- **Integration with Precision Agriculture:** Coupling nano-agrochemicals with drones, sensors, and AI-based monitoring tools for site-specific application, thereby minimizing waste and maximizing efficiency (Ali *et al.*, 2023; Yin *et al.*, 2023).
- **Improved Risk Assessment:** Developing standardized protocols for evaluating nanoparticle toxicity, persistence, and life-cycle impacts to build trust among regulators and consumers (Chhipa, 2022).
- **Cost Reduction and Scalability:** Advancing large-scale, low-cost production techniques to make nano-formulations affordable for farmers in developing regions (Lee *et al.*, 2022).

Conclusion:

Nano-pesticides and nano-herbicides represent a paradigm shift in crop protection, offering solutions to the inefficiencies and environmental burdens of conventional agrochemicals. By enhancing bioavailability, enabling controlled release, and reducing off-target losses, they hold significant potential to transform modern agriculture into a more sustainable and efficient system. However, challenges related to environmental safety, regulation, scalability, and public perception must be addressed to ensure responsible deployment.

The coming decade is likely to witness rapid advancements in agri-nanotechnology, driven by interdisciplinary research, policy support, and integration with precision agriculture. If coupled with green design principles and robust regulatory frameworks, nano-pesticides and nano-herbicides can play a pivotal role in achieving global food security while minimizing ecological footprints.

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Integrated Approaches in Agriculture Engineering

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