ADVANCES IN PLANT SCIENCES: RESEARCH AND APPLICATIONS



Editors

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Preface

Advances in Plant Sciences: Research and Applications is an edited volume that brings together diverse and contemporary research in plant sciences, agriculture, environmental management, medicinal plants, biological modelling, and sustainable resource utilization. Plants are fundamental to food security, ecological balance, human health, and economic development. In the face of climate change, soil degradation, pollution, biodiversity loss, and increasing resource demands, innovative and sustainable approaches in plant sciences are increasingly important.

The book begins with a comparative study of organic and conventional agriculture, focusing on crop productivity, soil health, and sustainability. It highlights the importance of agricultural practices that balance productivity with long-term environmental protection. The chapter on organic farming, spatial justice, and food sovereignty further broadens this discussion by examining the social and economic dimensions of sustainable agriculture and the challenges associated with agrarian marginalisation.

Plant biochemistry and medicinal applications are explored through the chapter on plant secondary metabolites, covering polyphenols, flavonoids, anthocyanins, and betacyanins. These naturally occurring compounds have considerable significance in nutrition, health, pharmaceutical research, and biotechnology. A detailed review of Mimosa pudica L. examines its pharmacognosy, phytochemistry, and pharmacological properties, highlighting the continuing importance of medicinal plants as valuable biological resources.

Environmental sustainability is an important theme of the volume. The chapter on endophytes in phytoremediation of heavy metals discusses biological approaches for reducing environmental contamination and supporting sustainable agriculture. The contribution on bioremediation strategies in AMR-polluted environments addresses the emerging problem of antimicrobial-resistance contamination and highlights the potential of biological methods for

environmental management.

The interdisciplinary scope of the book is further demonstrated through mathematical models in biology and medicine, showing how mathematical approaches can help explain biological processes and support scientific prediction and analysis. The survey and documentation of aromatic plants at Mata Jija Bai Government P.G. College, Indore, emphasizes the importance of documenting local plant diversity and conserving valuable botanical resources.

The volume also considers biomass as a sustainable energy source, discussing biomass resources, conversion technologies, and future prospects. This contribution highlights the potential of renewable biological resources in meeting energy requirements and promoting sustainable development.

Collectively, the chapters demonstrate the broad and interconnected nature of modern plant sciences. The book provides perspectives ranging from sustainable agriculture and plant metabolites to medicinal plants, biodiversity, environmental remediation, mathematical modelling, and renewable energy. These contributions underline the importance of interdisciplinary research in addressing contemporary scientific and environmental challenges.

This volume is intended for researchers, academicians, teachers, students, agricultural scientists, environmental professionals, and readers interested in plant sciences and their applications. It is hoped that Advances in Plant Sciences: Research and Applications will serve as a useful academic resource and encourage further research, innovation, and sustainable practices for the benefit of agriculture, environment, and society.

Editors

Advances in Plant Sciences: Research and Applications

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Comparative Dynamics of Organic and Conventional Agriculture: Impacts on Crop Productivity, Soil Health and Sustainability

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Abstract

This chapter offers a thorough, methodical examination of organic farming systems and their various effects on soil biogeochemical characteristics, plant productivity, and global food security metrics. We assess the ongoing "yield gap," which varies from 15% to 25% across key crop categories, and describe the micro and macro-ecological causes that underlie this discrepancy by combining data from multi-decade field trials and international meta-analyses. Conventional agriculture produces substantial soil degradation and ecological externalities even when it increases volumetric yield through artificial fertilizer fluxes. On the other hand, organic production frameworks improve soil organic carbon (SOC) stocks, long-term climate resilience, and below-ground biodiversity by utilizing intricate plant-soil-microbiome interactions. This chapter provides a cohesive framework for reducing the productivity gap through diversification strategies by outlining the structural trade-offs between immediate high-input agronomic yields and long-term agroecological vitality.

Introduction

The overuse of artificial fertilizers and poisonous pesticides in agricultural production has reached a dangerous level throughout the last three to four decades in order to feed the expanding population in India and throughout the world. The ecology, soil, and human health are all negatively impacted. Nowadays, people are

more conscious of the need to maintain both food quality and a healthy environment. Organic farming has become the only viable option for maintaining human-environmental harmony and providing a healthy diet for the world's expanding population. India is a global giver of organic farming. Four millennia of agricultural knowledge have enriched the farmers here, and organic farming has supported and fostered them during that time.

"Organic farming is that method of agriculture in which sustainable crop production is achieved by keeping the soil healthy and living, using only organic waste, organic and bacterial manures, and maintaining coordination with nature." When done correctly, organic farming is a sustainable method of production that uses natural resources and processes:

- The proper utilization of natural resources in the area.
- Making efficient use of the biological potential of sunlight and other living things.
- Preservation of soil fertility.
- The cyclical reuse of plant nutrients and organic materials.
- Total prohibition on any inputs that are harmful to the environment, including chemicals and genetically engineered species.
- Respect and equality for all living things, including animals, as well as the preservation and advancement of biodiversity.

Organic farming does not take advantage of soil-borne materials or degrade soil fertility because its entire technique is founded on harmony with natural processes and understanding of their interdependence. Soil is a living thing throughout the whole organic farming process, and all of the creatures that live there are the primary organs of the soil's fertility, helping to maintain fertility.

Modern agricultural science's primary goal is to minimize serious environmental degradation while simultaneously increasing crop productivity to meet the world's expanding food demand. In order to get beyond natural soil constraints and produce high immediate yields per hectare, conventional farming (CF) methods have relied on extensive applications of chemical pesticides, phosphorus fertilizers, and synthetic nitrogen for decades (Azarbad, 2022).

However, this high-input paradigm has resulted in systemic ecological implications, such as increased greenhouse gas emissions, rapid soil erosion, biodiversity loss, and water eutrophication.

With the goal of closing nutrient loops by reintroducing organic residues, animal manures, and nitrogen generated from legumes to the terrestrial matrix, organic farming has emerged as a legally regulated substitute that completely removes synthetic inputs (Lori et al., 2017). Despite these notable ecosystem services, the lower productivity profile and high yield variability of organic plant production continue to be major obstacles to its widespread scaling (Smith et al., 2019). The

architectural foundations of plant production in both contexts are assessed in this chapter.

Benefits of Organic Farming

- **Stability in Soil Fertility:** Stability in soil fertility: Using natural fertilizers, composting, and crop rotation are examples of organic farming techniques that help sustain soil nutrients over time. Organic techniques improve the soil's structure, water retention, and microbial activity by enriching it with organic matter rather than depleting it with artificial fertilizers. Long-term productivity and better crops are thus guaranteed.
- **Pollution-Free Farming:** Organic farming minimizes hazardous chemical runoff into rivers, lakes, and groundwater by eschewing synthetic fertilizers and pesticides. Beneficial insects, birds, and soil creatures are among the biodiversity that it safeguards. As a result, the environment is safer and cleaner for both people and wildlife.
- **Less Water Needed:** Organic matter, which functions as a sponge and holds water better, is abundant in organic soils. Compared to conventional farming, where chemical fertilizers frequently deteriorate soil structure, this lessens the need for frequent irrigation. This is a significant benefit in areas with limited water resources.

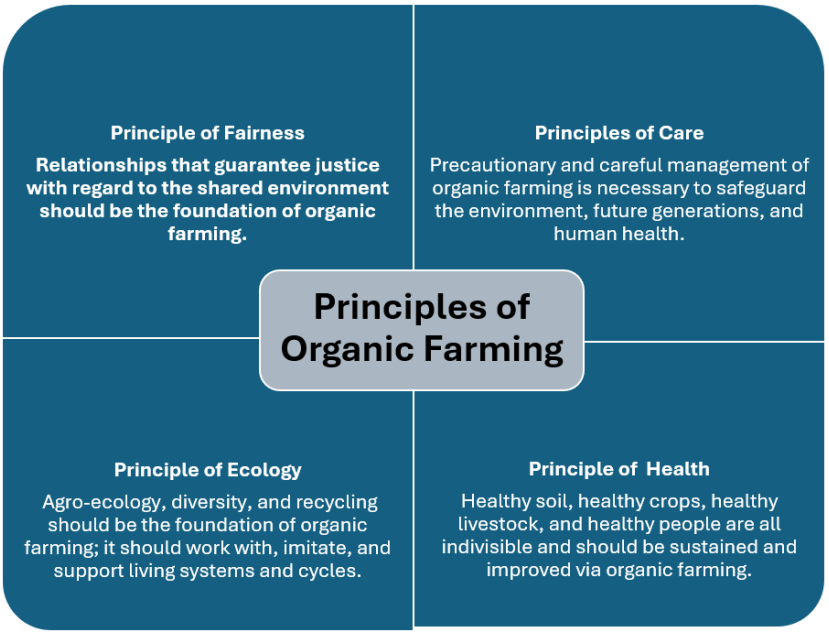


Fig 1. Principles Of Organic Farming

- **Lower Expenses and Higher Profits:** Reduced reliance on expensive chemical inputs (fertilizers, insecticides, and herbicides) results in lower costs and increased revenues for farmers. The lower input costs and higher market prices

for organic products boost profitability, even if organic farming may initially involve more labour. Healthier soil eventually lessens the need for outside inputs, which lowers expenses even further.

- **High-Quality Yield:** Health-conscious people are drawn to organic produce because it is frequently fresher, tastier, and devoid of chemical residues. Farmers and distributors may now command higher prices due to the increasing demand for organic products in both domestic and international markets. A sustainable cycle of production and consumption is thus established.

The Yield Gap: Evaluating Differences in Productivity

Organic plant production is fundamentally criticized for having a poorer volumetric efficiency per unit of geographic area. Long-term research demonstrates that, in comparison to their high-input conventional equivalents, organic systems show clear yield deficiencies.

Heterogeneity in Space and Species

According to global meta-analyses, the organic yield gap is firmly between 15% to 25% for all combined crop types (Juroszek, 2026; de Ponti et al., 2012). However, significant variations within particular plant families are hidden by this macro-statistic:

- **Cereals and Tubers:** Under organic management, yields of non-leguminous annuals including wheat, maize, and potatoes sometimes decrease by 30% to 40%, exhibiting some of the greatest decreases (Juroszek, 2026; Lin & Hülsbergen, 2017). The large, coordinated nitrogen spikes needed for these crops' jointing and booting stages are the cause of this development; slow-release organic fertilizers are unable to reliably provide this delivery profile.

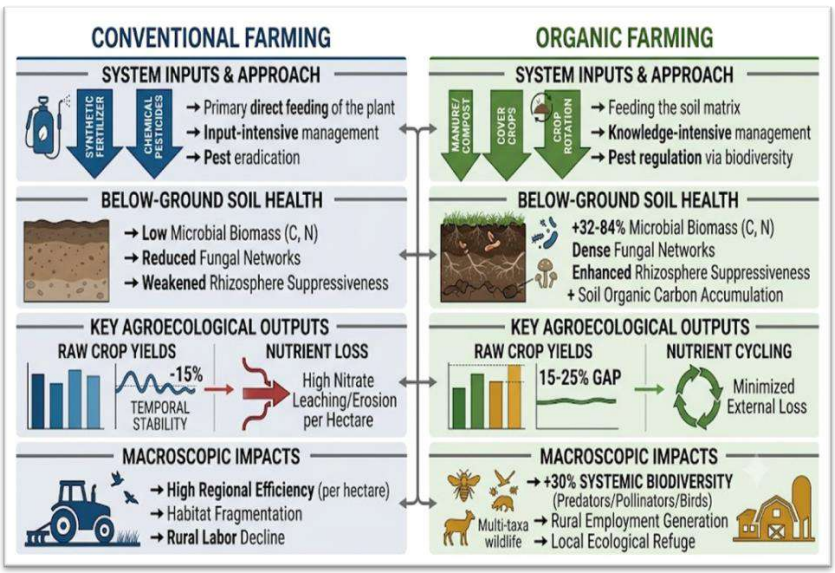


Fig 2 Intregated Comprative Dynamics of Agricultural Systems

- **Legumes:** Certain crops, such as alfalfa, peas, and soybeans, show little yield disparity and sometimes reach parity with traditional benchmarks (Juroszek, 2026). These species avoid reliance on external, manmade mineral nitrogen supplies because they have symbiotic interactions with nitrogen-fixing bacteria.
- **Perennials and Pollinator-Dependent Crops:** Fruits and some oilseeds exhibit intermediate yield gaps because the increased pollinator populations typical of organic landscapes are beneficial to their long-term root structures and dependence on insect vectors.

  A crucial indicator of food security is crop output stability across several seasonal cycles, which goes beyond absolute averages. According to meta-analyses, compared to conventional setups, organic agronomy shows about 15% less temporal stability, which results in noticeably greater yield variability from year to year (Knapp & van der Heijden, 2018; Smith et al., 2019). Organic crops are more susceptible to unforeseen pest outbreaks or unpredictable weather patterns because they are intrinsically more dependent on ambient biological ecosystem services.

  Importantly, when there is severe climate stress, this vulnerability reverses. Long-term experiments show that organic systems can function better than conventional ones during extreme drought circumstances (Azarbad, 2022). The physical characteristics of organically managed soils, which gradually build up greater amounts of organic matter and increase their capacity to hold water and maintain plant hydration during protracted dry spells, are directly linked to this structural resistance (Li et al., 2019).

Rhizosphere Microbiome and Soil Biogeochemistry

The basic workings of organic plant production change the emphasis from feeding the plant directly through water-soluble ions to feeding the living soil matrix.

1. Microbial Diversity, Enzymatic Velocity, and Abundance

The below-ground community is drastically altered by the removal of synthetic biocides and the ongoing application of carbon-rich inputs (composts, cover crop green manures). Globally, compared to traditionally managed soils, organic systems contain 32% to 84% more microbial biomass carbon and nitrogen (Lori et al., 2017).

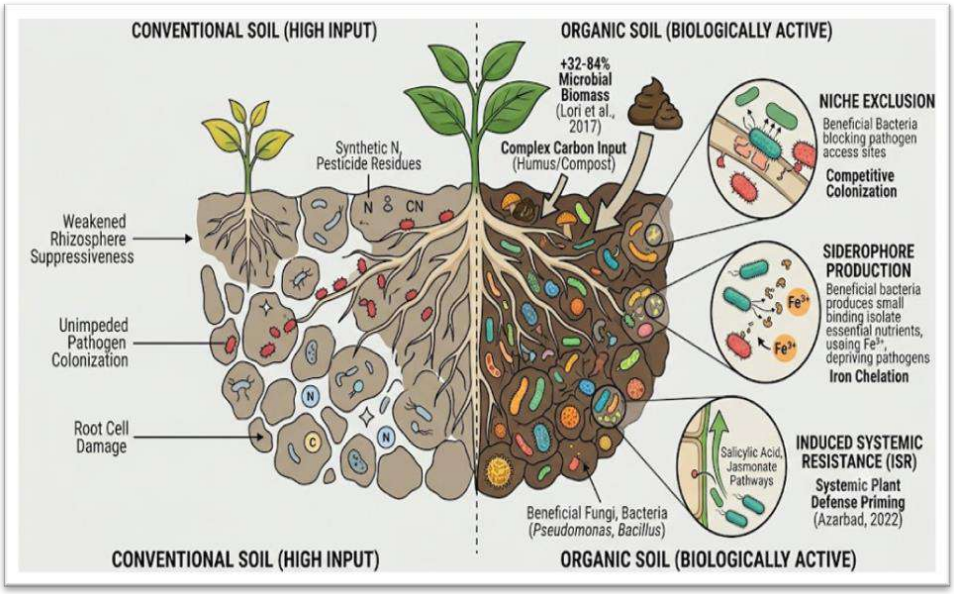


Fig 3 Rhizosphere Supperessiveness and Biocontrol Mechanism in Organic Soils

This biological change is accompanied by increased levels of extracellular microbial enzymes, especially dehydrogenase, urease and protease (Lori et al., 2017). Proteases hydrolyze complex proteins into bioavailable peptides and amino acids, and ureases hydrolyze nitrogenous matter into ammonia. This process creates a microbial driven efficient nutrient mineralization pipeline (Ahmed, 2025). Furthermore, organic management improves bacterial and fungal diversity and changes community structures to be more heterogeneous, as demonstrated by high throughput omics sequencing (Ahmed, 2025; Bertola et al., 2021).

2. Suppressiveness of Rhizosphere and Defence of Plant

Soil suppressiveness" is encouraged by the hyper-diverse microbiome of an organically managed soil, a condition in which soil-borne pathogens are biologically suppressed by competing non-pathogenic microorganisms. This happens via a few different paths:

- **Niche Exclusion:** Beneficial microbes quickly colonize root surfaces, blocking entry of harmful pathogens.
- **Siderophore Production:** Helpful bacteria take away vital nutrient pathogens need to grow by sequestering available iron.
- **Induced Systemic Resistance (ISR):** The constant association with non-pathogenic root-colonizing organisms prepares the plant's internal defence pathways, enhancing its ability to resist future pest attacks (Azarbad, 2022).

Nutrient Synchronization and Ecological Trade Offs

The environmental profile of organic plant production is characterized by a clear trade-off between spatial and efficiency.

1. Lack of Fit Problem Nitrogen Mineralization

In conventional systems, mineral nitrogen (〖"NH" 〗_4^+ and 〖"NO" 〗_3^-) is applied in highly concentrated, easily absorbed forms exactly when the crop needs it. Organic fertilizers, by contrast, depend entirely on microbial activity to convert pools of organic nitrogen to inorganic ions that are plant available. This leads to a synchronization problem: if the peak period of microbial mineralization is not aligned with the plant's maximum growth phase, the crop suffers acute nutrient deficiency, directly reducing the final yield.

2. Nitrate Leaching and Area and Product Dimensions

The paradox demonstrates that although organic farming is excellent at lowering environmental stress per hectare locally, its lower yield necessitates the conversion of more area to agriculture worldwide in order to match conventional outputs. According to Azarbad (2022) and Paarlberg (2022), this can result in indirect land-use changes like forest clearing, which releases stored soil organic carbon into the atmosphere.

Table 1 Environmental Impact of This Nitrogen Dynamics Depends on the Unit of Measure Use

Metric Evaluation	Organic Management System	Conventional Management System	Ecological Implication
Area-Based Nitrate Leaching (NO_3^-)	Significantly Lower (28% median reduction)	High per hectare	Organic farming helps to decrease the risk of groundwater contamination in the region (Sanders & Hess, 2019).
Product-Based Nitrate Leaching	Often Higher per ton of harvest	Lower per unit of product	Lower organic yields can lead to equal or greater leaching per ton of food produced compared to conventional systems (Rupp, 2026; Biernat *et al.,* 2020).
Soil Seepage and Structure	Higher water seepage due to macro-porosity	Reduced infiltration; high runoff	Organic matter improves porosity of the soils, which helps water infiltration but requires good timing of tillage to avoid leaching (Rupp, 2026).

Closing the Yield Gap via Agroecological Diversification

In the past, the yield gap was thought to be an unchangeable aspect of organic farming. Modern agroecological research, however, shows that some management changes might reduce this productivity gap without compromising environmental advantages.

1. Extended Crop Rotations and Multi Cropping

The application of two particular diversification strategies within organic systems can significantly reduce the yield gap, according to a seminal worldwide meta-analysis assessing more than 1,000 crop observations (Ponisio et al., 2015)

- **Multi-Cropping (Polyculture):** Spatial niche separation is maximized when many crop species are grown concurrently on a same plot. With this method, the organic yield gap is reduced to 9%±4% (Ponisio et al., 2015).
- **Structured Crop Rotations:** The yield gap is reduced to 8%±5% when different temporal sequences of crops are designed, especially those that alternate deep-rooted non-legumes with nitrogen-fixing cover crops (Ponisio et al., 2015).

By optimizing internal nutrient cycling and naturally suppressing weed populations, these focused tactics enable organic farmers to make their system extremely competitive with traditional single-crop monocultures.

Macroscopic Ecosystem Services and Systemic Biodiversity

The advantages of growing organic plants go far beyond the rhizosphere, impacting the macroscopic richness of nearby flora and wildlife. In increasingly fragmented, industrialized agricultural landscapes, organic agriculture serves as an ecological haven. (Mader and others, 2002)

In comparison to conventional fields, organic farms maintain an average of 30% higher species richness and 50% higher overall abundance of organisms, according to thorough multi-taxa meta-analyses (Bengtsson et al., 2005; Hole et al., 2005). This increase in biodiversity is evident at a number of important trophic levels:

- **Arthropod Predators:** Without chemical pesticides, populations of parasitoid wasps, carabid beetles, and spiders flourish, offering dependable, integrated pest management (Crowder et al., 2010).
- **Pollinator Communities:** The fruit set of neighboring insect-pollinated crops is directly enhanced by the increased stability and diversity of wild bee and hoverfly populations (Kennedy et al., 2013).
- **Avian and Floral Populations:** Long-term population decreases observed in industrialized farming zones can be reversed by maintaining non-crop weed species near field borders, which offer farmed birds vital nesting places and food supplies (Hole et al., 2005).

Potential for Global Scaling and Economic Viability

The financial sustainability of organic plant production for farmers and its overall macroeconomic viability are critical factors in any widespread shift.

1. The Price Premium and Financial Competitiveness

Despite lower crop yields and higher labor requirements (7% to 25% higher cost), organic farming is 22% to 35% more profitable than conventional farming, according to a thorough worldwide assessment of the financial performance of organic farming across five continents (Crowder & Reganold, 2015). Market price premiums the higher retail prices customers pay for organic goods are the only factor driving this economic advantage.

The benefit-cost ratios for organic farms are far higher than those of conventional systems when these premiums are taken into account. Organic farming is still financially viable and offers rural farmers a steady income even if price premiums somewhat decline (Crowder & Reganold, 2015).

2. The Food Security Matrix for the Twenty-First Century

Researchers employ balanced, multi-criteria frameworks to determine if organic agriculture can grow to fulfill the demands of global food security. Environmental sustainability, soil health restoration, financial return per hectare, and reducing human pesticide exposure are all areas where organic agronomy excels (Reganold & Wachter, 2016). However, a complete worldwide transition to organic farming would include fundamental adjustments in human consumption patterns because it takes more land to produce the same amount of food. This would entail drastically cutting down on food waste worldwide and substituting plant-based nutrition for land-intensive animal proteins in human diets (Mueller et al., 2017).

Conclusion

Conventional plant production and organic farming are essentially different methods of managing agricultural land. In order to increase crop productivity in the short term, conventional farming depends heavily on external inputs, which can have negative long-term effects on soil health and the ecosystem. Organic farming, on the other hand, invests in the biological health of the soil matrix, promoting a variety of rhizosphere microbiomes and dependable climate resilience, but frequently at the expense of an initial yield decrease of 15% to 25%. Over the past few decades, India's agricultural production—particularly food production has grown significantly. Modern methods, artificial fertilizers, and sophisticated seed varieties were initially responsible for this accomplishment. However, over use of chemicals and hazardous fertilizers in the rush to enhance output has started to degrade soil fertility and worsen environmental contamination. Since people are currently compelled to eat food that is contaminated with chemicals, modern farming faces the difficulty of producing food that is in line with human health.

This yield gap is not a fixed constraint. Organic systems can maintain their primary environmental advantages while achieving competitive yields by implementing agroecological diversification techniques including multi-cropping, intricate crop rotations, and the use of precise microbial biofertilizers. Global agricultural policy should avoid making a strict decision between these two frameworks going forward. Rather, future food security will probably depend on combining the ecological wisdom of organic soil management with the resource efficiency of contemporary technologies.

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Plant Secondary Metabolites: An Overview of Polyphenols, Flavonoids, Anthocyanins and Betacyanins

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Abstract

Plant secondary metabolites are structurally diverse bioactive compounds that play essential roles in plant defense, adaptation, and ecological interactions. Although they are not directly involved in primary metabolic processes, these metabolites contribute significantly to protection against pathogens, ultraviolet radiation, and oxidative stress. Among the major classes, polyphenols, flavonoids, anthocyanins, and betacyanins have attracted considerable scientific interest because of their diverse biological activities and therapeutic potential. These compounds exhibit strong antioxidant, antimicrobial, antiviral, anti-inflammatory, cardioprotective, and anticancer properties, making them valuable for pharmaceutical, nutraceutical, cosmetic, and food applications. Their biosynthesis is regulated mainly through the shikimate, phenylpropanoid, and flavonoid pathways and is influenced by genetic and environmental factors. Recent advances in phytochemistry and biotechnology have improved the understanding of their biosynthesis, biological functions, and potential applications. This review summarizes on polyphenols, flavonoids, anthocyanins, and betacyanins, and highlights their significance in plant biology and human health.

Keywords: Secondary metabolites, Polyphenols, Flavonoids, Anthocyanins, Betacyanins, Antioxidants, Medicinal plants.

Introduction

Plants synthesize a wide variety of secondary metabolites that are not directly involved in primary metabolic processes such as growth, development, or reproduction but play indispensable ecological and physiological roles. These compounds protect plants against pathogens, herbivores, ultraviolet radiation, and

other environmental stresses, while also contributing to pigmentation, pollination, and plant–microbe interactions. Owing to their remarkable structural diversity and biological activities, plant secondary metabolites have attracted considerable attention in plant science, medicine, biotechnology, and the pharmacological, nutraceutical, cosmetic, and food industries. Among the major classes of secondary metabolites, polyphenols, flavonoids, anthocyanins, and betacyanins are particularly important because of their potent antioxidant, antimicrobial, antiviral, anti-inflammatory, cardioprotective, and anticancer properties (Rice-Evans et al., 1997; Serkedjieva and Ivancheva, 1999; Taiz and Zeiger, 2006). These bioactive compounds are synthesized primarily through the shikimate, phenylpropanoid, and flavonoid biosynthetic pathways and contribute significantly to plant adaptation, defense mechanisms, and ecological interactions. This chapter presents an overview of polyphenols, flavonoids, anthocyanins, and betacyanins.

Polyphenols

Polyphenols constitute one of the largest groups of plant secondary metabolites and are characterized by the presence of multiple phenolic hydroxyl groups attached to aromatic rings. Besides naturally occurring compounds, synthetic and semi-synthetic polyphenols have also been developed for biomedical applications (Cui et al., 2010). More than 10,000 phenolic compounds have been identified in plants, including phenolic acids, flavonoids, tannins, lignans, and anthocyanidins, demonstrating their remarkable structural diversity (Taiz and Zeiger, 2006).

The biosynthesis of polyphenols primarily occurs through the shikimate and phenylpropanoid pathways, with the shikimate pathway serving as the principal route for the production of most plant phenolics (Taiz and Zeiger, 2006). Besides contributing to plant metabolism, phenolic compounds influence several physiological processes, including protein synthesis and nitrogen metabolism. Hydroxycinnamic acids such as cinnamic, p-coumaric, and caffeic acids act as important intermediates in chlorogenic acid biosynthesis and other phenolic metabolic pathways (Grace et al., 1998).

Polyphenols are recognized for their potent antioxidant properties and their ability to neutralize reactive oxygen species (ROS), thereby protecting cellular components from oxidative damage. Their capacity to inhibit oxidative modification of low-density lipoproteins (LDL) has been associated with reduced risks of cardiovascular diseases and atherosclerosis (Rice-Evans et al., 1997). In addition, numerous polyphenols exhibit antiviral activity and have demonstrated therapeutic potential against several viral pathogens (Serkedjieva and Ivancheva, 1999). Phenolic-rich medicinal plants such as Crataegus monogyna and Crataegus laevigata possess cardioprotective properties, including improved myocardial contractility, reduced reperfusion arrhythmias, peripheral vasodilation, and antioxidant activity (Zhang et al., 2001; Kirakosyan et al., 2003). Furthermore, several phenolic compounds

interact with plant hormones and enzymes, thereby influencing plant growth and development. However, certain phenolic constituents particularly condensed and hydrolysable tannins may also exert antinutritional effects under specific conditions (Butler, 1992). An increased level of polyphenols noticed in the investigations of Patil and Gaikwad (2013) are found beneficial to improve the antiviral, antioxidant and myocardial activity of this medicinally important Simarouba glauca.

Flavonoids

Flavonoids represent one of the most abundant classes of polyphenolic secondary metabolites and are widely distributed throughout the plant kingdom. These compounds possess a characteristic C6–C3–C6 carbon skeleton comprising two aromatic rings connected by a three-carbon bridge. More than 4,000 flavonoids have been identified, including flavones, flavonols, flavanones, flavanols, isoflavones, anthocyanins, catechins, and chalcones (Rice-Evans et al., 1996).

Flavonoid biosynthesis begins with chalcone synthase, which produces tetrahydroxychalcone as the common precursor for the synthesis of various flavonoid subclasses. Structural diversity is generated through hydroxylation, methoxylation, glycosylation, and methylation reactions.

In plants, flavonoids perform numerous physiological and ecological functions. They protect tissues from harmful ultraviolet-B radiation by accumulating in epidermal cells, where they selectively absorb UV wavelengths while permitting visible light transmission (Taiz and Zeiger, 2006). Flavonoids also contribute to defense against pathogens, facilitate communication during legume–Rhizobium symbiosis, and attract pollinators through flower pigmentation (Parr and Bolwell, 2000). In addition, anthocyanin biosynthesis, responsible for red, purple, and blue pigmentation in plants, originates from the flavonoid pathway (Taylor and Grotewold, 2005).

Dietary flavonoids are abundant in fruits, vegetables, seeds, flowers, and nuts, forming an essential component of the human diet. Epidemiological and experimental studies have consistently demonstrated that high flavonoid intake is associated with reduced risks of cardiovascular disease, cancer, and other age-related disorders (Verhoeyen et al., 2002). Their biological activities include antioxidant, anti-inflammatory, antiallergic, antiviral, and anticarcinogenic effects. Mechanistically, flavonoids scavenge reactive oxygen and nitrogen species, inhibit lipid peroxidation, prevent LDL oxidation, and modulate oxidative stress-related enzymes (Jadhav et al., 2008). The study indicates that the increased levels of flavonoids in response to foliar application of growth regulators might be helpful to defense against pathogen or may protect against UV-B radiations (Patil and Gaikwad 2013).

Anthocyanins

Anthocyanins are water-soluble flavonoid pigments responsible for the red, pink, purple, and blue coloration of flowers, fruits, leaves, and other plant organs. These pigments play a critical ecological role by attracting pollinators and seed-dispersing organisms. Chemically, anthocyanins are glycosylated derivatives of anthocyanidins, with glycosylation enhancing pigment stability and solubility (Taiz and Zeiger, 2006).

Anthocyanin biosynthesis proceeds through interconnected shikimate, phenylpropanoid, and flavonoid pathways and is strongly influenced by carbohydrate availability, particularly sucrose, as well as environmental conditions such as light intensity, temperature, water availability, and phytohormones (Loreti et al., 2008). Besides contributing to plant coloration, anthocyanins protect tissues from ultraviolet radiation, deter herbivores, and function as potent antioxidants capable of scavenging reactive oxygen species (Gould, 2004 and Nagata et al., 2003).

Betacyanins

Betacyanins are nitrogen-containing water-soluble pigments belonging to the betalain family and occur mainly in members of the order Caryophyllales. Unlike anthocyanins, betacyanins are chemically distinct and often replace anthocyanins in families such as Amaranthaceae, Cactaceae, Nyctaginaceae, and Portulacaceae. These pigments are induced by developmental signals, light, and wounding and perform physiological functions comparable to those of anthocyanins (Zhao et al., 2011)

In addition to imparting attractive red and pink coloration, betacyanins have gained commercial importance as natural food colorants due to their low toxicity and high stability. Their strong antioxidant activity contributes to various health-promoting effects, while betanin, the principal betacyanin pigment, has demonstrated promising anticancer and free radical-scavenging properties (Tesoriere et al., 2004 and Lee et al., 2005). Environmental factors and plant growth regulators have also been shown to regulate betacyanin biosynthesis through modulation of DOPA-4,5-dioxygenase (DODA) gene expression (Zhao et al., 2011).

Conclusion

Plant secondary metabolites constitute a diverse group of bioactive compounds that are essential for plant survival, adaptation, and defense against biotic and abiotic stresses. Among them, polyphenols, flavonoids, anthocyanins, and betacyanins play significant physiological roles while exhibiting a wide range of biological activities, including antioxidant, antimicrobial, antiviral, anti-inflammatory, cardioprotective, and anticancer effects. Advances in phytochemical research and biotechnology have expanded our understanding of their biosynthesis, regulation, and therapeutic potential. Owing to their safety, natural origin, and multifunctional properties, these

compounds have gained considerable importance in pharmaceutical, nutraceutical, cosmetic, and food industries. Future research integrating metabolomics, molecular biology, and biotechnological approaches will further facilitate the sustainable utilization of plant secondary metabolites and support the development of novel therapeutic agents and functional products.

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Mimosa pudica L: A Review of Its Pharmacognosy, Phytochemistry and Pharmacological Properties

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Abstract

Mimosa pudica L., commonly known as the sensitive plant or touch-me-not, is a medicinal herb belonging to the Fabaceae family. The plant is widely distributed in tropical and subtropical regions and has been extensively used in traditional medical systems, including Ayurveda, Siddha, Unani, and folk medicine. This review aims to provide a comprehensive overview of the botanical characteristics, phytochemical constituents, traditional uses, and pharmacological activities of *Mimosa pudica*. Phytochemical investigations have revealed the presence of diverse bioactive compounds, including alkaloids, flavonoids, tannins, terpenoids, saponins, glycosides, phenolic compounds, coumarins, and other secondary metabolites, which contribute to its therapeutic properties. Various Iin vitro and Iin vivo studies have demonstrated a broad spectrum of pharmacological activities, including antioxidant, anti-inflammatory, antimicrobial, wound-healing, antidiabetic, hepatoprotective, antinociceptive, antiulcer, antidepressant, antimalarial, antivenom, diuretic, and antifertility effects. Experimental studies employing models such as carrageenan-induced paw edema, streptozotocin-induced diabetes, carbon tetrachloride-induced hepatotoxicity, forced swimming test, and Plasmodium berghei infection have provided scientific evidence supporting its traditional applications. The extensive ethnomedicinal use and diverse biological activities of *Mimosa pudica* highlight its potential as a valuable source of bioactive compounds for the development of novel therapeutic agents. Further studies focusing on toxicity, standardization, and clinical evaluation are required to fully establish its medicinal significance.

Keywords: *Mimosa pudica*, sensitive plant, phytochemistry, ethnomedicine, pharmacological activities, medicinal plants.

Introduction

Mimosa pudica L., commonly known as the sensitive plant, touch-me-not, or shame plant, is a medicinal herb belonging to the Fabaceae family. It is known by various vernacular names, including Thottavadi in Malayalam, Lajawanti in Hindi, Hadergitthe in Kannada, Kasirottam in Tamil, and Manugumaramu in Telugu. The plant is native to Central and South America, particularly Brazil, but has become widely distributed as a pantropical weed throughout the world. It thrives in tropical and subtropical regions of the Americas, the southern United States, Africa, Australia, and South Asia. In India, *Mimosa pudica* is commonly found growing wild throughout the country. [1,2,3,13,18]

One of the most remarkable characteristics of *Mimosa pudica* is its ability to exhibit rapid leaf-folding movements in response to external stimuli such as touch, heat, vibration, or mechanical disturbance. In addition to this rapid thigmonastic movement, the plant also displays slower periodic leaf movements regulated by an internal biological clock. These unique physiological responses have attracted considerable scientific interest and contributed to its recognition as an important medicinal and research plant. [2,3,13,14]

Traditionally, all parts of the plant have been used in various systems of medicine, including Ayurveda and folk medicine, for the treatment of numerous ailments such as dysentery, leprosy, asthma, inflammation, fatigue, burning sensations, blood disorders, and gynecological conditions. Recent scientific investigations have further validated many of these traditional uses and revealed a broad spectrum of pharmacological activities, including antioxidant, antibacterial, antifungal, anti-inflammatory, antidiabetic, anticonvulsant, antidepressant, antimalarial, antitumor, antiulcerogenic, hepatoprotective, immunomodulatory, wound-healing, diuretic, antifertility, and antivenom effects. [1,3,6,9,13,17]

The therapeutic potential of *Mimosa pudica* is largely attributed to the presence of diverse bioactive phytochemicals, including flavonoids, tannins, alkaloids, phenolic compounds, glycosides, and terpenoids. These compounds have been reported to contribute significantly to the plant's biological and medicinal activities. [12,14,17,19]

Therefore, this review aims to provide a comprehensive overview of the available literature on the botanical characteristics, phytochemical composition, pharmacological activities, and potential therapeutic applications of *Mimosa pudica*, highlighting its significance as a valuable medicinal plant and identifying areas for future research.

Botanical Profile

Taxonomy

The formal classification of *Mimosa pudica* L. places it firmly within the Fabaceae (legume) family, an economically important group. The Mimosoideae subfamily is

characterized by its actinomorphic (radially symmetrical) flowers arranged in dense, showy capitula, with numerous, conspicuous stamens. Its detailed classification is as follows: [2,14]

Kingdom: Plantae

Order: Fabales

Family: Fabaceae

Subfamily: Mimosoideae

Genus: *Mimosa*

Species: *Mimosa pudica*



Fig. 1: Mimosa pudica

Distribution and Habitat

Mimosa pudica is native to Central and South America and is believed to have originated in Brazil. However, it has become widely naturalized throughout tropical and subtropical regions of the world and is considered an invasive species in several areas, including South Asia, Southeast Asia, Tanzania, and many Pacific Islands.

The plant grows in a wide variety of soil types and can survive even in soils with low nutrient content. It is commonly found in disturbed habitats such as roadsides, construction sites, wastelands, grasslands, and cultivated fields, where it may occur as individual plants or form dense thickets. *Mimosa pudica* generally requires disturbed soil for successful establishment and is highly sensitive to shade; consequently, it rarely grows beneath dense forest canopies.

The roots of the plant produce carbon disulfide, which may inhibit the colonization of the rhizosphere by certain mycorrhizal and pathogenic fungi. The species is typically found from sea level up to an elevation of approximately 1,300 m and thrives in regions receiving annual rainfall ranging from 1,000 to 2,000 mm. As a tropical species, *Mimosa pudica* is sensitive to frost and grows best under warm climatic conditions. [2,13,14]

Pharmacognostical Description

Mimosa pudica L. is a small, diffuse, creeping perennial herb belonging to the family Fabaceae, although it may behave as an annual under certain environmental conditions. The plant is often suffrutescent, becoming woody at the base with age, and typically attains a height of50–70 cm.

The stems are slender, cylindrical, well-branched, and longitudinally grooved, with a light brown to greyish-brown exterior. They are armed with sharp, recurved prickles and covered with fine bristles, while the fibrous bark can be easily separated from the wood. The leaves are alternate, bipinnately compound, and highly sensitive to external stimuli. Each leaf consists of one to two pairs of pinnae bearing 15–25 pairs of small, linear-oblong leaflets. The leaflets are green to yellowish green, almost glabrous, and arranged oppositely along the rachis. Stipules are present at the base of the petiole.

The flowers are small, pink to lilac in color, and arranged in globose axillary heads measuring approximately 1–1.5 cm in diameter. Numerous prominent stamens impart a fluffy appearance to inflorescence. The calyx is minute with ovate-oblong lobes, while the corolla is pink and delicate. Pollination occurs primarily through insects (entomophily) and, to a lesser extent, by wind (anemophily). The fruit is a dry loment (a modified legume) measuring about 1–1.6 cm in length and 0.4–0.5 cm in width. At maturity, it fragments into 2–5 indehiscent, one-seeded segments. The margins of the fruit bear yellowish, spreading bristles that facilitate seed dispersal by adhering to animal fur, clothing and other surfaces. The seeds are small, hard, and brown in color. [2,13,14]

Leaflet Movement Physiology

Mimosa pudica is a thigmonastic plant that exhibits rapid movements in response to various external stimuli, including touch, vibration, wind, wounding, electrostimulation, drought, changes in illumination, and thermal stimuli. Upon stimulation, the leaflets fold inward, and the petioles droop downward.

The plant also exhibits nyctinastic movements, commonly known as sleep movements. During the evening or in darkness, the leaflets fold together, and the entire leaf droops downward, while reopening occurs at sunrise or under sufficient light conditions. These rhythmic movements are regulated by an internal biological clock and are influenced by environmental light cues.

In addition to nyctinastic responses, *Mimosa pudica* displays seismonastic movements, which occur in response to mechanical stimuli such as touch, shaking, or warming. The stimulus can be transmitted to adjacent leaves, resulting in coordinated leaf closure throughout the plant. These movements serve as a protective mechanism against herbivores and environmental disturbances.

The rapid folding of the leaves is mediated by specialized motor organs called pulvini, located at the base of the petioles and leaflets. Stimulation generates an

electrical signal that triggers the rapid movement of ions and water out of the motor cells, causing a sudden loss of turgor pressure. As a result, the cells collapse temporarily, leading to leaflet closure and petiole drooping. Once cellular turgor is restored, the leaves gradually return to their original position. [3,13]

Phytochemical Constituents

Phytochemical investigations of *Mimosa pudica* have revealed the presence of a diverse range of bioactive compounds that contribute to its medicinal and pharmacological properties. Various phytochemical analyses have demonstrated that different parts of the plant contain numerous secondary metabolites, including alkaloids, flavonoids, tannins, terpenoids, steroids, saponins, phenolic compounds, quinones, glycosides, jasmonic acid, and coumarins. These phytochemicals are believed to be responsible for the plant's wide spectrum of biological activities, such as antioxidants, antimicrobial, anti-inflammatory, antidiabetic, and wound-healing effects.

Preliminary phytochemical screening has also identified the presence of primary metabolites, including carbohydrates, proteins, amino acids, fatty acids, and oil. In addition, the leaves of *Mimosa pudica* contain several important bioactive constituents, such as D-pinitol, an inositol derivative, mimosamine, mimosinic acid, and the non-protein amino acid mimosine. [3,12,14,19] Various phytochemical analyses and preliminary tests have been performed to identify and confirm the presence of phytochemicals and primary metabolites in *Mimosa pudica*. Some of these tests are:

Alkaloids

To identify the presence of alkaloids, the samples are extracted from various parts of the plant and samples are diluted in hydrochloric acid solution. Different tests are conducted to identify and confirm the presence of alkaloids:

Table 1: Qualitative tests for the detection of alkaloids in Mimosa pudica extracts. [12,19]

S.No	Name of the test	Procedure	Observation
1	Mayer's test	Test solution + Mayer's reagent	Yellow cream precipitate
2	The Wagnerian experiment	Test solution + Wagner's reagent	Brown/reddish-brown precipitate
3	Dragendroff test	Test solution + dragendroff reagent	Crimson precipitate
4	Hager's test	Test solution + Hager's reagent	Yellow color in precipitate

Tannins

Qualitative test conducted for the detection and confirmation of tannins are:

Table 2. Qualitative tests for the detection of tannins in Mimosa pudica extracts. [12,15,19]

S.No	Name of the test	Procedure	Observation
1	Gelatin test	Extract treated with 1% gelatin solution containing sodium chloride	White precipitate
2	Vanillin-hydrochloric acid test	Extract + few drops of vanillin hydrochloride reagent	Red color is developed

Flavonoids

Qualitative test conducted for the detection and confirmation of flavonoids in M. pudica are:

Table 3. Qualitative tests for the detection of flavonoids in Mimosa pudica extracts. [12,14]

S.No	Name of the test	Procedure	Observation
1	Lead acetate test	Extract + lead acetate solution	Yellow precipitate
2	Alkaline reagent test	Extract + sodium hydroxide solution + dilute acid	Formation of an intense yellow color that becomes colorless upon addition of dilute acid.
3	Shinoda test	Extract + magnesium turnings + concentrated hydrochloric acid	Magenta or pink color

Saponins

Tests were conducted by dissolving the extract with water and mixed thoroughly. Later the test conducted are:

Table 4. Qualitative tests for the detection of saponins in Mimosa pudica extracts. [15,19]

S.No	Name of the test	Procedure	Observation
1	Froth test	Extract diluted with distilled water and shaken vigorously in a graduated cylinder for 15 minutes	Formation of a stable froth layer indicates the presence of saponins
2	Liebermann–Burchard test	Extract treated with chloroform and filtered	Formation of a brown ring at the junction of

		+ acetic anhydride + concentrated H_2SO_4 along the side of the test tube	the two layers indicates the presence of steroidal saponins

Glycosides

After the samples are extracted and hydrolysed with dilute hydrochloric acid, glycosidic assays areconducted.

Table 5. Qualitative tests for the detection of glycosides in Mimosa pudica extracts. [19]

S.No	Name of the test	Procedure	Observation
1	Modified Borntrager's Test	Extract + ferric chloride solution + boiled in a water bath for 5 min + cooled + mixed with an equal volume of benzene + benzene layer separated and treated with ammonia solution.	Pink or cherry-red color in the ammoniacal layer indicates the presence of anthranol glycosides
2	The Legal's Examination	Extract + sodium nitroprusside in pyridine + methanolic alkali	Pink to crimson red color indicates the presence of cardiac glycosides
3	Killer killiani Test	Dried extract + glacial acetic acid containing ferric chloride; carefully layered with concentrated H_2SO_4	Formation of a brown ring at the interface indicates the presence of cardenolides (cardiac glycosides)

Carbohydrates

The diluted extracts were individually filtered and used to prepare the sample solution by adding distilled water. The filtrates were then subjected to phytochemical analysis to determine the presence of carbohydrates.

Table 6. Qualitative tests for the detection of carbohydrates in Mimosa pudica extracts. [19]

S.No	Name of the test	Procedure	Observation
1	Molisch's test	Filtrate + alcoholic α-naphthol + concentrated H_2SO_4 along the sides of test tube	Formation of a violet/purple ring at the junction

2	Benedict test	Filtrate + Benedict'sreagent heated in a water bath	Red precipitate
3	Fehling's test	Filtrate + Fehling's A and Fehling's B solutions	Brick red precipitate

Proteins and Amino acids

Preparation of the Test Solution: Test solution extract was dissolved in water and mixed thoroughly.

Table 7. Qualitative tests for the detection of Proteins and Amino acids in Mimosa pudica extracts. [19]

S.No	Name of the test	Procedure	Observation
1	Million's test	Extract + Millon's reagent and heated gently	Formation of a white precipitate that turns red upon heating
2	Biuret test	Extract + 10% sodium hydroxide solution + 0.7% copper sulphate solution	Violet or reddish-violet color
3	Ninhydrin test	Extract + 0.25% ninhydrin reagent and heated for a few minutes	Blue or purple color

Fatty Acid and Oil

Table 8. Qualitative tests for the detection of fatty acid and oil in Mimosa pudica extracts. [19]

S.No	Name of the test	Procedure	Observation
1	Examination of the stain	A small quantity of extract is pressed between two filter papers	Formation of a permanent oily stain on filter paper
2	Soap test	Extract heated with 0.5 N alcoholic potassium hydroxide solution in a water bath for 15 minutes	Formation of soap

Terpenoids/Steroids

To identify the presence of terpenoids/steroids, the Salkowski test is conducted. To the plant extract mix 2 ml of chloroform and 3 ml of conc. H_2SO_4 are added. A reddish-brown color is formed, indicating the presence of terpenoids/steroids. [15]

Phenolic Compounds

To identify the presence of phenolic compounds, ferric chloride test is conducted. To the extract, a few drops of neutral ferric chloride solutions are added. Bluish black color is formed indicating the presence of phenolic compounds. [19]

Traditional Uses of *Mimosa pudica*

Mimosa pudica has been widely used in traditional systems of medicine, including Ayurveda, Siddha, Unani, and various folk medicinal practices, for the treatment of numerous diseases and disorders. Different parts of the plant, such as the leaves, roots, stems, flowers, fruits, and seeds, possess medicinal properties and have been employed for therapeutic purposes.

Traditionally, the plant has been used for the management of headache, migraine, anxiety, stress, insomnia, epilepsy, and other nervous disorders owing to its calming and neuroprotective effects. It is also valued for its anti-inflammatory, analgesic, antimicrobial, hemostatic, and wound-healing properties.

In addition, *M. pudica* has been used in the treatment of gynecological disorders, urinary tract infections, diarrhea, dysentery, piles, jaundice, and respiratory ailments such as asthma and bronchitis. The plant is also believed to improve blood circulation, enhance mood, and promote tissue regeneration. [1,2,3,13]

In Ayurveda, *Mimosa pudica* is considered cooling in nature and is believed to balance the Pitta and Kapha doshas. The roots are described as bitter, acrid, cooling, vulnerary, and alexipharmic, and are traditionally used in the treatment of leprosy, dysentery, vaginal and uterine disorders, inflammations, burning sensations, asthma, migraine, diabetics, leukoderma, fatigue and blood-related diseases.

It is also prescribed for general weakness and impotence. In the Unani system of medicine, the roots are regarded as resolvent and alterative and are used for conditions arising from blood and bile disorders, including bilious fever, piles, jaundice and leprosy.

Root decoctions are commonly used as a gargle to relieve toothache and are also employed in the treatment of diarrhea, amoebic dysentery, bleeding piles, and urinary infections. [1,13]

The extensive traditional use of *Mimosa pudica* across different medicinal systems highlights its therapeutic importance and supports the need for further scientific investigations to validate its pharmacological activities and clinical applications. Many of the traditional uses of *Mimosa pudica* have been scientifically validated through in-vivo and in-vitro studies.

Experimental investigations using animal models have confirmed several pharmacological activities of the plant, including anti-inflammatory, antidiabetic, hepatoprotective, wound-healing, antinociceptive, antidepressant, antimalarial, and antiulcer effects. [1,13]

These activities have been evaluated using various experimental models such as carrageenan-induced paw edema, cotton pellet granuloma assay, streptozotocin-

induced diabetic rat model, carbon tetrachloride (CCl_4)-induced hepatotoxicity model, anti-nociceptive activity test, gastrointestinal motility determination, antipyretic activity test, screening of hypoglycemic activity, Elevated plus maze test (EPMT), Light-dark box test (LDBT), Forced swimming test (FST), Tail suspension test (TST), Passive avoidance (PA) test. [1,3,7]

The results of these studies provide scientific support for the traditional medicinal applications of *Mimosa pudica* and highlight its potential as a source of bioactive therapeutic compounds.

Table 9. Traditional medicinal uses of different parts of Mimosa pudica.

S. No	Plant parts	TraditionalMedicinally used
1	Leaves	Wound healing, hemorrhages, conjunctivitis, hemorrhoids, hydrocele, rheumatism, antibacterial and anti-inflammatory applications.
2	Roots	Dysentery, diarrhea, fever, jaundice, ulcers, asthma, leprosy, leukoderma, inflammations, piles, fistula, gynecological disorders, urinary infections.
3	Leaves and seed (decoction)	Urinary tract infections, diuretic activity, urinary complaints.
4	Flowers	wound healing and blood purification
5	Seeds	urinary disorders and reproductive health
6	Stem	wound dressing and treatment of inflammatory conditions
7	Whole plant	Rheumatism, edema, myalgia, epilepsy, elephantiasis, insect repellent, antimicrobial applications

Pharmacological Activities

Mimosa pudica possesses a broad spectrum of pharmacological and biological activities, which are largely attributed to the presence of diverse bioactive phytochemicals. Numerous studies have reported the therapeutic potential of various parts of the plant, including the leaves, roots, stems, and seeds, in the treatment and management of a wide range of diseases. [1,3,6,11,13,19]

Experimental and pharmacological investigations have demonstrated that *Mimosa pudica* exhibits antioxidant, anti-inflammatory, antimicrobial, antidiabetic, wound-healing, hepatoprotective, anticonvulsant, antidepressant, antitumor, and several other medicinal properties. The following sections summarize the major pharmacological activities reported for *Mimosa pudica* and the possible mechanisms underlying these effects. [1,3,14,17,19]

Antioxidant Activities

The antioxidant activity of *Mimosa pudica* has been widely attributed to its high content of phenolic and flavonoid compounds, which can scavenge free radicals and

reduce oxidative stress. Several studies have reported that the antioxidant potential of *M. pudica* extracts is concentration-dependent and is primarily associated with the presence of polyphenolic constituents. [1,3,6,15,17,19]

The antioxidant activity of crude extracts obtained from the aerial parts and leaves of *M. pudica* has been evaluated under in-vitro conditions using various free radical scavenging assays. Ethanolic extracts have demonstrated significant antioxidant activity in assays such as 2,2-diphenyl-1-picrylhydrazyl (DPPH), nitric oxide (NO), and 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) radical scavenging models. [6,15,17,19]

The DPPH assay evaluates the ability of plant extracts to donate hydrogen atoms and neutralize stable free radicals, while the nitric oxide scavenging assay is particularly important because excessive production of nitric oxide has been implicated in inflammation, carcinogenesis, and other pathological conditions. [15,16,17]

In addition, the chloroform extract of *M. pudica* leaves has been assessed using superoxide radical scavenging, nitric oxide scavenging, DPPH radical scavenging, and reducing power assays. The extract exhibited remarkable free radical scavenging activity and demonstrated antioxidant potential comparable to that of the standard antioxidant, ascorbic acid. [15,17]

Anti-Inflammatory Activities

Chronic inflammation is associated with the development of various diseases. One of the major pharmacological properties of *Mimosa pudica* is its anti-inflammatory activity, which is believed to be associated with the presence of bioactive phytochemicals, particularly flavonoids and other phenolic compounds. [1,3,14,17]

The anti-inflammatory potential of *M. pudica* has been evaluated in several experimental animal models. In one study, petroleum ether, ethanolic, and aqueous extracts of the plant were assessed using carrageenan-induced paw oedema and cotton pellet granuloma models in male albino rats. The extracts were administered at doses ranging from 50 to 200 mg/kg, while indomethacin (10 mg/kg) was used as the standard anti-inflammatory drug. All three extracts exhibited significant anti-inflammatory activity when compared with the control group. [1,2,11,13]

In another experiment, whole-plant extracts of *M. pudica* were administered at doses of 200, 400, and 800 mg/kg produced dose-dependent anti-inflammatory effects in albino rats. The highest level of inhibition was observed at a dose of 800 mg/kg, indicating a strong anti-inflammatory response at higher concentrations. [1,11,13]

The observed anti-inflammatory activity may be attributed to the presence of flavonoids and other phytoconstituents capable of suppressing inflammatory mediators and reducing tissue inflammation. The whole plant, stems, leaves, and

seeds of *M. pudica* Linn. showed strong antioxidant capacity, and leaf extract is the strongest, and stem extracts are the weakest. [11,13,17]

Antimicrobial Activities

The antimicrobial activity of *Mimosa pudica* has been attributed to the presence of various bioactive constituents, including terpenoids, flavonoids, glycosides, alkaloids, quinones, phenolic compounds, tannins, saponins, and coumarins. These phytochemicals are known to possess inhibitory effects against a wide range of pathogenic microorganisms and contribute significantly to the medicinal value of the plant. [1,2,3,6,8,16,19]

Several studies have evaluated the antimicrobial potential of different parts of *M. pudica*. In one study, shade-dried leaves, roots, and stem bark were separately extracted using ethanol and petroleum ether and tested against the bacterium *Staphylococcus aureus* and the fungus *Aspergillus niger*. Both extracts exhibited inhibitory effects on the growth of these microorganisms, indicating promising antimicrobial activity. [6,8,12,16]

Another study assessed petroleum ether, chloroform, and methanolic extracts prepared from the aerial and underground parts of the plant using the disc diffusion method. The extracts were tested against a variety of bacterial and fungal species, including *Bacillus cereus*, *Bacillus subtilis, Bacillus megaterium, Staphylococcus aureus, Pseudomonas aeruginosa, Escherichia coli, Salmonella typhi, Shigella dysenteriae, Candida albicans, Aspergillus niger*, and *Saccharomyces cerevisiae*. Although some extracts exhibited limited or weak inhibitory effects, the results suggested variability in antimicrobial activity depending on the extraction solvent and the microorganism tested. [6,12,16]

Further studies demonstrated that chloroform, ethyl acetate, and methanolic extracts of the leaves, roots, and pods possess significant antimicrobial properties. Among these, the chloroform extract showed the strongest antibacterial activity against several Gram-positive and Gram-negative bacteria, while the ethyl acetate extract exhibited notable antifungal activity. [6,12,16,19]

The extracts were also found to inhibit the growth of microorganisms such as *Aspergillus fumigatus, Citrobacter divergens*, and *Klebsiella pneumoniae*. Moreover, both methanolic and aqueous extracts have been reported to possess appreciable antifungal activity, further supporting the traditional use of M. pudica in the treatment of microbial infections. [8,12,16]

The antimicrobial effects of *M. pudica* are believed to result from the synergistic action of its phytochemical constituents, which may disrupt microbial cell membranes, inhibit essential enzymes, interfere with metabolic pathways, and suppress microbial growth. [1,3,6,8,12,16,19]

Wound-Healing Activities

Wound healing is a complex biological process involving inflammation, proliferation, and remodeling of damaged tissues. Numerous studies have demonstrated the wound-healing potential of *Mimosa pudica*, which is primarily attributed to its rich content of phenolic compounds, flavonoids, and tannins. These phytochemicals are known to promote tissue repair, enhance wound contraction, and facilitate the regeneration of damaged tissues. [1,3]

Studies on the roots of *M. pudica* have indicated that phenolic compounds, particularly tannins, play a significant role in the wound-healing process. The high tannin content of the roots is believed to contribute to wound repair through their astringent properties, which help in wound contraction, reduction of bleeding, skin diseases, and protection against microbial infections. [1,3,13]

In a study, a hydrogel formulation containing a hydroalcoholic extract of *Mimosa pudica* was developed using a suitable polymeric base. Qualitative phytochemical screening of the extract revealed the presence of alkaloids, flavonoids, tannins, glycosides, and proteins, all of which are associated with wound-healing activity. The formulated hydrogel was found to be compatible with the normal pH of the skin and suitable for topical application without causing irritation. The study concluded that the *M. pudica* hydrogel possesses promising properties for topical wound management. [1,3,5]

Several studies have also evaluated methanolic and aqueous extracts of *M. pudica* incorporated into simple ointment bases at concentrations of 0.5%, 1%, and 2% (w/w). Among these formulations, the 2% (w/w) methanolic and aqueous extracts exhibited the most significant wound-healing activity, which was attributed to the presence of phenolic constituents and other bioactive compounds. [4,13,14]

Furthermore, the wound-healing efficacy of ethanolic extracts of *Mimosa pudica* has been investigated in mouse models with deep dermal excision wounds. The extracts were administered at doses of 50, 100, 150, and 200 mg/kg of body weight prior to wound induction. Treatment with *M. pudica* significantly enhanced wound contraction and accelerated the healing process in a dose-dependent manner. The highest level of wound closure and reduction in healing time was observed at higher doses, demonstrating the plant's effectiveness in promoting tissue repair. [4,5,20]

Antidiabetic Activities

Diabetes mellitus is a chronic metabolic disorder characterized by persistent hyperglycemia resulting from impaired insulin secretion, insulin action, or both. The antidiabetic activity of *Mimosa pudica* has been evaluated in several experimental studies. In one investigation, streptozotocin-induced diabetic male albino rats weighing 150–200 g were administered ethanolic extracts of *M. pudica* at a dose of 500 mg/kg body weight. [1,3]

The study was conducted over a period of eight weeks, and the results demonstrated a significant reduction in fasting blood glucose levels in the treated animals

compared with the diabetic control group. These findings indicated that *M. pudica* possesses notable hypoglycemic activity. Various parts of the plant, including the leaves, roots, and stems, have been investigated for their ability to regulate blood glucose levels. Among the different extracts tested, the ethanolic extract exhibited the most pronounced antidiabetic effect. The extract significantly reduced plasma glucose concentrations and showed an efficacy profile comparable to that of standard oral hypoglycemic agents. [1,3,10]

The antidiabetic activity of *Mimosa pudica* is believed to be associated with the presence of bioactive phytochemicals such as flavonoids, phenolic compounds, alkaloids, and D-pinitol, which may enhance glucose utilization, improve insulin sensitivity, and reduce oxidative stress associated with diabetes. [10,14]

Hepatoprotective Activities

The liver plays a vital role in metabolism, detoxification, and the maintenance of physiological homeostasis. Several studies have demonstrated the hepatoprotective potential of *Mimosa pudica*, which is largely attributed to its antioxidant properties. [1]

The hepatoprotective activity of *M. pudica* has been investigated using carbon tetrachloride (CCl_4)-induced hepatotoxicity models in Wistar rats. In one study, ethanolic leaf extracts of *Mimosa pudica* were administered to animals subjected to CCl_4-induced liver injury. Treatment with the extract significantly reduced the elevated levels of liver function markers, including serum glutamate pyruvate transaminase (SGPT), serum glutamate oxaloacetate transaminase (SGOT), alkaline phosphatase (ALP), total bilirubin (TB), and direct bilirubin (DB). [1,2,3,14]

The hepatoprotective effect observed was comparable to that of silymarin, a standard hepatoprotective drug. Furthermore, administration of *M. pudica* extract restored both enzymatic and non-enzymatic antioxidant levels that had been depleted by CCl_4-induced oxidative stress. The extract also significantly reduced lipid peroxidation, as evidenced by decreased lipid peroxide levels, thereby protecting hepatic tissues from oxidative damage. [1,2,3]

The hepatoprotective activity of *Mimosa pudica* is believed to result from its rich content of flavonoids, phenolic compounds, and other antioxidant phytochemicals, which help neutralize reactive oxygen species and stabilize cellular membranes. The ethanolic extract exhibited significant dose-dependent hepatoprotective and antioxidant effects, suggesting its potential role in preventing or alleviating chemically induced liver damage. [3,14]

Antinociceptive Activities

The antinociceptive activity of ethanolic leaf extracts of *Mimosa pudica* has been evaluated using the hot plate test, tail flick test, and acetic acid-induced writhing assay. In both the hot plate and tail flick tests, the extract significantly increased the latency period, indicating analgesic activity. Similarly, in the acetic acid-induced

writhing model, the extract produced a significant reduction in the number of writhing responses. These findings suggest that *Mimosa pudica* possesses notable antinociceptive activity, which may be attributed to the presence of flavonoids and other bioactive phytochemicals. [3,11]

Antiulcer Activities

Mimosa pudica has been reported to possess significant antiulcer and gastroprotective activity in various experimental models, including aspirin-induced, alcohol-induced, and pylorus ligation-induced gastric ulcers. Studies have shown that ethanolic and methanolic extracts of the plant significantly reduced ulcer formation, as evidenced by a lower ulcer index, and improved protection of the gastric mucosa. [1,14]

In pylorus ligation models, the ethanolic leaf extract exhibited a dose-dependent reduction in total gastric acidity and ulcer severity, along with an increase in gastric pH. These findings suggest that *M. pudica* possesses both cytoprotective and antisecretory properties, supporting its traditional use in the treatment of gastric ulcers and other gastrointestinal disorders. [2,13]

Antidepressant Activities

Mimosa pudica has been traditionally used in Mexico for the management of depression. Several experimental studies have demonstrated the antidepressant potential of its aqueous leaf extract in animal models. Administration of the extract significantly reduced immobility time in the forced swimming test and improved performance in the differential reinforcement of low-rate response (DRL-72s) test.

The antidepressant effects observed were comparable to those produced by standard drugs such as clomipramine and desipramine. In addition, the extract exhibited anxiolytic-like activity in the elevated plus maze test, indicating its potential to alleviate anxiety-related symptoms. These findings suggest that *Mimosa pudica* possesses antidepressant and anxiolytic properties and may serve as a promising natural therapeutic agent for the management of mood disorders. [1,3,9]

Antimalarial Activities

Malaria remains a major parasitic disease worldwide, particularly in tropical and subtropical regions. The antimalarial potential of *Mimosa pudica* has been investigated using experimental models of Plasmodium infection. Ethanolic leaf extracts of *M. pudica* were evaluated against Plasmodium berghei-infected mice and demonstrated significant antiplasmodial activity in various antimalarial screening models. [2]

Phytochemical analysis of the extract revealed the presence of bioactive constituents such as terpenoids, flavonoids, and alkaloids, which are known to possess antimalarial properties. The observed antiplasmodial activity is believed to be associated with the synergistic action of these phytochemicals. These findings

suggest that *Mimosa pudica* may serve as a potential source of natural antimalarial agents and warrant further investigation into the development of novel antimalarial therapeutics. [2,13]

Antivenom Activities

Mimosa pudica has been reported to possess promising antivenom activity against snake envenomation. Studies have shown that alcoholic extracts and tannin-rich fractions of the plant can effectively neutralize the toxic effects of snake venoms. In experimental models, tannins isolated from *M. pudica* provided significant protection against *Naja kaouthia* venom, with treated animals exhibiting improved survival and reduced mortality when compared with conventional antivenom treatments. [1,3]

The aqueous root extract of *M. pudica* has also been evaluated for its ability to inhibit various venom-induced toxic effects, including lethality, phospholipase activity, edema formation, fibrinolytic activity, and hemorrhagic activity caused by Naja naja and *Bungarus caeruleus* venoms. The antivenom effect is primarily attributed to the presence of polyphenolic compounds, particularly tannins, which can interact with venom proteins and reduce their toxicity. [2,3]

Iin vitro studies have demonstrated that *M. pudica* tannins exhibit a greater neutralizing effect against Naja kaouthia venom than commercial tannic acid. These findings suggest that *Mimosa pudica* possesses considerable antivenom potential; however, further studies are required to establish its efficacy, safety, and clinical applicability in the treatment of snakebite envenomation. [1,3,13]

Diuretic Activities

Mimosa pudica has long been used in traditional medicine for its diuretic properties, with its roots commonly employed to promote urine production and treat urinary tract disorders. Decoctions prepared from its leaves and seeds have also been used for the management of urinary tract infections. Phytochemical analyses of the aqueous leaf extract have revealed the presence of bioactive compounds such as alkaloids, tannins, and saponins, which may contribute to its therapeutic effects. Experimental studies in Wistar rats demonstrated that ethanolic extracts and leaf decoctions significantly increased urine output and enhanced the excretion of electrolytes, particularly sodium (Na^+) and chloride (Cl^-) ions. [3,14,18]

The diuretic effect was comparable to that of the standard drug furosemide. Furthermore, higher doses of the extract did not produce toxicity or mortality during a 14-day study period, suggesting a favorable safety profile. [14,18]

Antifertility Activities

Mimosa pudica has been traditionally used in India as an antifertility agent. Experimental studies have demonstrated that the methanolic root extract of M. pudica exerts significant effects on reproductive functions in Swiss albino mice.

Administration of the extract altered the levels of key reproductive hormones, including luteinizing hormone (LH), follicle-stimulating hormone (FSH), prolactin, estradiol, and progesterone, thereby affecting the regulation of the estrous cycle. [1,2,18]

Treatment with the root extract was found to prolong the diestrus phase and delay the estrous cycle, particularly at a dose of 300 mg/kg body weight. These hormonal alterations adversely affected reproductive performance and resulted in reduced fertility and a decreased number of litters produced.

The observed antifertility effect is believed to be associated with the disruption of normal hormonal regulation of reproduction. Overall, these findings indicate that *Mimosa pudica* possesses significant antifertility activity and may have potential applications in the development of plant-based contraceptive agents. [2,3,13,18]

Toxicity and Safety Considerations

Despite the wide range of pharmacological activities exhibited by *Mimosa pudica*, information regarding its safety profile remains limited. Traditional reports and some literature sources suggest that indiscriminate consumption of *M. pudica* may be associated with toxic effects. Therefore, the use of crude plant preparations should be approached with caution, particularly for internal administration. [3,13,14]

The use of *M. pudica* during pregnancy and lactation is generally not recommended due to the lack of adequate safety data. Furthermore, information regarding its safety in young children and individuals with severe hepatic or renal disorders remains insufficient. Consequently, medical supervision is advisable before prolonged or therapeutic use of the plant. [13,14]

Although several Iin vitro and Iin vivo studies have demonstrated significant pharmacological activities and reported no acute toxicity at certain experimental doses, comprehensive toxicological evaluations and long-term safety studies are still lacking. Most available evidence is derived from laboratory and animal studies, and well-designed clinical trials in humans are limited. [3,13]

Conclusion

Mimosa pudica is a widely used medicinal plant in traditional healthcare systems and is recognized for its rich phytochemical composition, including alkaloids, flavonoids, tannins, phenolic compounds, terpenoids, saponins, and glycosides. These bioactive constituents are closely associated with the plant's broad range of pharmacological effects.

Scientific investigations reported in the review provide experimental support for multiple therapeutic activities, such as antioxidant, anti-inflammatory, antimicrobial, wound-healing, antidiabetic, hepatoprotective, antinociceptive/antiulcer, antidepressant/anxiolytic, antimalarial, antivenom, and diuretic properties. Overall, the combined findings from Iin vitro and Iin vivo

studies suggest that *Mimosa pudica* has significant potential as a natural source of bioactive compounds.

However, most of the current evidence is still derived from laboratory and animal models. To translate this promise into safe and effective healthcare applications, future research should focus on comprehensive phytochemical standardization, detailed toxicity assessments, mechanism-based studies, and well-designed clinical trials. In summary, *Mimosa pudica* represents a valuable medicinal resource with strong prospects for future drug discovery and development.

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Organic Farming, Spatial Justice and Food Sovereignty: Reconsidering Agrarian Marginalisation

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Abstract

Organic farming is a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity, and cycles adapted to local conditions rather than inputs with adverse effects. It seeks to organise crop and livestock production in conditions that remain closely aligned with natural ecological cycles. The chemical-intensive model linked with the Green Revolution has generated serious environmental and public-health concerns; the extensive use of toxic farm inputs has produced damaging consequences for Indian and Turkish societies with horrible repercussions. Spatial justice is employed here as an analytical lens for assessing dominion, unequal power relations and the marginalisation of farming communities. The influence of neoliberalism has also weakened the capability of the contemporary state to respond effectively, producing what may be understood as a crisis of authority. The study suggests that organic agriculture can offer an alternative pathway for reducing input dependence and addressing agrarian indebtedness. Equitable rights to produce food and to obtain safe and nutritious food are fundamental to spatial justice in rural areas.

Keywords: Organic farming, synthetic fertilisers, environment, health, nutrition, justice, marginalisation.

Introduction

The demand for organic products has increased substantially over the past few decades, partly because consumers associate organic food with safety and better health. In cumulative terms, global agriculture now produces more food grains than at any earlier point in human history, which seems to be sufficient to feed the world's total population of approximately 8.0 billion. Yet more than one billion people continue to experience hunger, and food insecurity remains widespread across developing regions where people have been isolated into the human body

population and biological body population. The rapid increase in immunity-related novel diseases compels us to think about the quality of the food that most of the population in Turkey and India is consuming. The situation is particularly serious in India, where severe agrarian distress has contributed to farmer suicides due to the changing scenario of the Green Revolution to the colourless neoliberal initiative. Although the Green Revolution generated a period of increased agricultural and economic output in both countries, by the mid-nineties, the taste began to turn bitter. Similarly, the economic rift between the haves and have-nots is expanding in Turkey at an alarming rate. Organic agriculture includes production practices for crops and livestock that emphasise ecological management and natural processes. The organic approach seeks to minimise or exclude synthetic chemicals, genetically modified inputs and artificial growth promoters used for food production and processing with respect to its high-value-added agribusiness. As a result of the constant developments in the agriculture sector, the population of both nations are facing considerable environmental loss and resulting health degradation. The chemical innovations of modern agriculture have proved catastrophic to the economic self-reliance and social-cultural fabric of farming communities in both countries. Shockingly, the increasing cases of abnormal sperm morphology and lower sperm count among young males, reproductive abnormalities, and miscarriages among young females are posing a serious threat, and it is paving the way for a dying civilisation if not stopped in time (Mittal et al., 2014).

The indicators presented in Table 1 determine the continuing expansion of organic agriculture worldwide. The latest FiBL survey describes 98.9 million hectares of organic agricultural land in 2024, equivalent to 2.1 per cent of global agricultural land, with 4.8 million organic producers worldwide. India has the largest number of organic producers, with 2,363,607 producers, and approximately 4.0 million hectares of organic agricultural land. These figures highlight India's growing importance in the global organic farming sector. Turkey and India have advantages for growth and sustainability in organic farming due to the favourable geographical conditions. Both countries have experienced a shift in the role of the state from welfare-oriented intervention towards a more limited regulatory function; therefore, this has contributed to limited attention to farmers lived experiences and social dimensions, as private actors become important investors and promoters in the organic sector of agriculture.

Table-1: Global Key Indicators of Organic Farming, 2024

Indicator	**World**	**Top Countries**
Countries with organic activities	183 countries	-
Organic	98.9 million hectares	Australia: 53.0 million ha; India: 4.0 million ha;

Indicator	World	Top Countries
agricultural land	(2024)	Argentina: 3.9 million ha
Organic share of total agricultural land	2.1%	Liechtenstein: 43.5%; Austria: 27.2%; Uruguay: 23.1%
Development of organic agricultural land, 2023-2024	-176,000 ha (-0.2%)	USA: +1.15 million ha (+56.0%); Guatemala: +241,744 ha (+193.0%); China: +169,350 ha (+5.0%)
Wild collection and further non-agricultural areas	25.5 million hectares (2024)	Finland: 6.9 million ha; China: 3.3 million ha; Zambia: 2.5 million ha
Producers	4.8 million producers	India: 2,363,607; Uganda: 404,246; Ethiopia: 203,258
Organic retail sales	€145.0 billion	USA: €60.4 billion; Germany: €17.0 billion; China: €15.5 billion
Per capita consumption	€17.7	Switzerland: €481; Denmark: €373; Austria: €292
Number of affiliates of IFOAM-Organics International (2025)	593 affiliates	Germany: 73; India: 39; USA: 36; Italy: 24; Switzerland: 22

Source: FiBL survey 2026, based on national data sources, from certifiers and IFOAM-Organics International.

Objectives and Research Questions

The study was undertaken with the following objectives:

- To examine the rationale and development of organic farming in Turkey and India.
- To identify the major controls and future opportunities for organic farmers.
- To examine the observations and experiences of farmers in Turkey and India.

The study addresses two principal research questions:

1. What are the dominant discourses related to the failures of the green revolution and organic farming that are going on in the Turkish and Indian societies?
2. What kind of political-economic relationship is developing between the state and agrarian society?

Research Methodology

This study adopted a qualitative research approach using the Extended Case Method (ECM). The Extended Case Method is a reflexive research approach that helps researchers understand social issues by linking field observations with existing theories (Burawoy, 1998). Instead of only describing events, it explains why and how they occur by connecting real-life experiences with theoretical concepts (Tavory & Timmermans, 2009). The method is useful for examining the relationship between society, politics, and economic change. According to Burawoy (1998), the Extended Case Method enables researchers to test and refine existing theories through detailed analysis of specific cases. Primary data were collected through semi-structured interviews, participant observation, and focus-group discussions with organic farmers, community leaders, and NGO representatives. The study covered organic farming areas in the Antalya Province and Aegean Region of Turkey, and the state of Punjab in India. Secondary data were collected from government reports, international organisations, books, and published research to support the analysis.

Reimagining Agrarian Subalternity Through Spatial Justice and Organic Farming

Edward Soja's concept of spatial justice provides the principal conceptual orientation for the analysis (Soja, 2009). Through the Extended Case Method, the study seeks to contextualise the analysis of spatial justice in the case of organic farming in both countries. The concept of spatial justice has been conceived by Henri Lefebvre, David Harvey, and Edward Soja and has mainly been applied by scholars in urban research; however, it has received comparatively less attention in analyses of rural justice. Soja (2009) explains why justice and injustice must be understood explicitly in spatial terms, not merely in the city but at all geographical scales. Though spatial justice is seen as both outcomes and process yet, the initial phase of the concept encompasses equality in delivery process in the space of socially valued resources and prospects to utilise them, further focuses on locational discrimination, environmental justice, the political organisation of space, exclusion, resistance, challenges posed by government programs, the pain of fragmenting communities and finally reflects on possible solutions by critically focusing on decision-making procedures (Soja 2009, 2010). Spatial justice approaches questions of justice through a geographical lens, and therefore, it brings it closer to social justice and space. Spatial justice can therefore be used to investigate how hybridity of inequalities is created and how hegemony and power relations affect the

marginalisation process of farming communities in Turkey and India. The research problems of this study are directly related to environmental justice, subalternity, failures of the green revolution, control of elite strategies over natural resources, and opportunities to access organic food for all sections of society.

Study Area Selection and Comparative Rationale

Both India and Turkey are major emerging economies that are also developing strategic and trade relations outside their immediate regions. India has rolled back rigid regulatory barriers on its private corporate sector and opened its economy to foreign direct investment (since 1980). Turkey occupies a strategic position between Asia, Europe, and Africa, and because of this character, scholars have even recommended calling Turkey a continent. Turkey has developed strong commercial links with Europe and now, increasingly, with India. Notably, Turkey and India signed a memorandum of understanding (in the year 2018) for extending cooperation through interaction among government agricultural institutions, scientists, agro-business, soil conservation, and above all, for the promotion of organic farming. Economic relations (Table-2) between Turkey and India are improving, though they have still to achieve their full potential. Historically, the massive influx of the Turkish population in India led to a luminous fusion of Indian and Islamic culture. The diplomatic missions between the Ottoman Sultan and the Muslim rulers of the Indian subcontinent date back to the fourteenth century. As members of the G-20, both countries have a crucial role in international economic cooperation. Moreover, India and Turkey have a shared geopolitical interest in the stability and security of Afghanistan, Pakistan, and the Middle East. While expressing his valuable views on Turkish nation-building in the early 1930s, Mustafa Kemal Ataturk emphasised that action should be taken not only based on past experiences but also on the needs of the present. This exhortation seems valid in Turkey-India relations for the better prospects of organic farming, mainly providing a market for organic products to one another. Both countries have increasingly recognised that it would be better to sell organic produce to each other instead of importing to developed countries where standards are quite high. The Government of India itself articulated on several occasions that chemical farming is calamitous for immunity and that it can be improved by using natural products.

Table 2: Bilateral Economic and Trade Relations Between Turkey and India (million USD)

Year	Export	Import	Volume	Balance
2015	650.3	5,613.5	6,263.8	-4,963.1
2016	651.7	5,757.2	6,408.9	−5,105.5
2017	758.5	6,216.6	6,975.1	−5,458.1
2018	1,121.5	7,535.7	8,657.2	-6,414.2

Year	Export	Import	Volume	Balance
2019	890.0	4,796.0	5,686.0	-3,907.0
2020	890.0	4,796.0	5,686.0	-3,906.0
2021	1,305.0	7,936.0	9,241.0	-6,631.0
2022	1,637.0	10,697.0	12,334.0	-9,060.0
2023	1,644.0	7,931.0	9,575.0	-6,287.0
2024	1,510.0	7,020.0	8,540.0	-5,510.0

Source: Republic of Turkey, Ministry of Foreign Affairs, Turkey-India Economic and Trade Relations.

The foundations of organic farming can be traced to traditional agricultural practices that evolved in villages of Turkey and India since humans settled in these regions. Additionally, these countries are regarded as the gene centres of many crops. Many traditional practices based on indigenous knowledge have gradually declined, which were strengthened over a long time through trial and error. Turkey has an estimated 12,000 plant species, whereas in Europe, the total number of plant species is approximately 13,000 (Tekeli & Gokce, 2016). India has a wide variety of plant species that no other country can boast of, with restricted biodiversity. India has more than 45,000 species of flora, of which several species are not found anywhere else in the world (Botanical Survey of India, 2018). The biological diversity of both countries indicates that these countries still have the potential for organic farming, as the flora is surviving even in the hard times of the Anthropocene. Moreover, Turkish and Indian agriculture is characterised by small land holdings and family-owned farms. Due to these facts, a large population has a close relationship with farming processes beneficial in organic farming.

Historical Development of Organic Farming in India and Turkey

The earlier idea of ecological agriculture gradually developed into the contemporary organic farming movement, alongside increasing commercialisation. British Scientist, Sir Albert Howard (1873-1947) is widely recognised as an important pioneer of the organic movement (Heckman, 2006). For more than twenty-six years, Howard researched organic farming in India. In his book An Agricultural Testament (Howard, 1943), Howard developed the principle known as 'The Law of Return', in which he supported the idea that all agricultural waste and sewerage sludge should be mixed with the soil and highlighted his invention of the 'Indore Method of Composting'. Howard also wrote that traditional Indian farming is superior to modern chemical farming in England. Furthermore, Rachel Carson's book, Silent Spring, strengthened the organic movement by convincing Western academia of the toxic repercussions of chemical agriculture (Beyl, 1992; Carson, 1962). Turkey has developed a considerable industrial economy in which the share of the agriculture sector is about 10 per cent of its gross domestic product (GDP), and this sector

supports over 46 per cent of the country's population for survival. Agriculture continues to play a major livelihood role in India, where it contributes about 14.6 per cent of GDP and supports more than 58 per cent of the Indian population directly (FAO, 2012; GOI, 2012). An average citizen of these countries spends nearly half of his total expenditure on food. Organic farming generally requires relatively high labour inputs; hence, it needs over 15 per cent more labour than industrial agriculture and can consequently create additional rural employment (Pandey & Singh, 2012). The literature review reveals findings such as organic farming increasing the income of farming communities and decreasing immigration among farm labour (OzbiLge, 2007). In India, women constitute an essential section of the labour as field workers, both in economically backward states such as Bihar, Madhya Pradesh, and Uttar Pradesh and economically advanced states like Haryana and Gujarat. Before the introduction of modern agriculture in Turkey and India, the entire cultivation was based on age-old practices incorporating almost all forms of organic matter, green leaves, crop waste, earthworm activity, animal bones, and other in situ biodegradable substances. Farmers were using whatever was feasible and locally available, and the concept of agricultural inputs from the markets was almost absent.

The early development of organic farming in Turkey was driven by export prospects to the European markets rather than domestic demand. Aegean region is the pioneer region where organic agriculture began in Turkey. Already existing processing companies served as a favourable reason for inertia in the Aegean region. A large share of production is exported from Izmir's seaport to different countries of the world. The organic farming enthusiasts formed a syndicate under the aegis of the Association of Organic Agriculture established in 1992, which provided institutional support. Later, this group also contributed to education and agricultural research, publications, and outreach activities in rural areas (Demirkol et al., 2003). The legal and regulatory powers were guaranteed through the Ministry of Agriculture and Rural Affairs (MARA). The concerned ministry published the regulation document named 'Organic Farming Principles and Applications Regulation' in the Official Gazette No. 24812 dated 11.7.2002.

The Ministry of Agriculture and Rural Affairs subsequently established the National Steering Committee of Organic Agriculture, which focuses on policy implementation and progress issues. An industrial advisory board provide input into policy determination and advances the technical improvement of the organic industry (Olhan et al. 2005). Growing international demand for organic produce in international markets led education institutions to start offering graduate-level programs in agriculture. The first professional school was opened in Kelkit to offer hands-on training-based courses in organic agriculture. In Turkey, 212 types of organic products are produced, which can be categorised into nine groups, including dried fruits, edible nuts, herbs and spices, fresh and processed fruits, vegetables,

pulses, oilseeds, cereals, and industrial crops (mainly cotton) (Nardali & Gencler, 2011). Most farmers are concentrating on the production of apples, dried fruits, hazelnuts, dried figs, olives, and raisins.

Following growing recognition of the adverse effects of chemical-intensive agriculture, the Ministry of Commerce started the National Organic Programme in India in 2000. The Agricultural and Processed Food Products Export Development Authority regulates the National Programme for Organic Production (Bhattacharyya and Chakraborty, 2005). Initially, organic production was oriented largely towards export markets and has been practised as contract farming agreements with MNC's (Ramesh et al., 2010). Over the past decade, the Indian middle class has become aware of the ill effects of the Green Revolution. Hence, demand for organic food has grown, and several outlets have been established in urban areas. NGO's and civil society are also supporting and promoting the production, marketing, and certification of natural food (Nardali and Gencler, 2011). As a result, organic farming has been realised as an increasingly important policy priority and has developed into a significant Pro-natural food and anti-genetically modified food movement. Interestingly, it has been confirmed from various research studies that Indian farmers are opting for organic farming not only for sustainability but also for higher economic returns.

Interpreting Agrarian Change Through Spatial Justice Farmers' Perceptions and Social Understandings

Synthetic fertilisers and pesticides were introduced in Turkey in the mid-sixties and subsequently expanded considerably over time. In India, DDT (Dichlorodiphenyltrichloroethane) was the first synthetic input provided by the government on a large scale to increase crop productivity in the early 1960s. In India, farmers are now applying so much nitrogen and phosphorus in their farms that water resources have been destroyed, which is causing serious health problems like mouth ulcers. The simple measure adopted by farmers is based on the principle of show-off and copying. If one puts one sack of urea (carbamide) in his field, then his next neighbour puts two sacks, and the application of fertiliser works with the mindset that more application means bumper production. Excessive nitrogen application can contribute to declining soil fertility resulting from blanket crop production technologies, including the excessive usage of chemicals. Fertilisers and pesticides may raise production over a limited period, but the chemical residue affects human health for centuries (Aktar et al., 2009). The industrial agriculture augmented the grain production and agriculturalists' turnover but also presented long-standing repercussions such as loss of human health and natural resources. In India, the average dietary consumption of pesticide residue is 32.5 mg per day for vegetarians and 356.5 mg per day per individual for non-vegetarians (Pandey & Singh, 2012). Unfortunately, traces of poisons have also been found in mother's

milk (Brown, 2013). Farming communities are exposed to multiple chemical substances in the form of pesticides, herbicides, fungicides, rodenticides, and poisons used in the post-harvesting process of food storage. They described their observations and personal experiences mainly related to the degrading male sperm quality, menstruation issues and miscarriages among females, and cases of abnormal and premature births. Similarly, it has been observed that there are cases of both early maturity and delayed maturity among the youth. Therefore, rising infertility cases are also affecting marriage relationships and creating numerous psychological problems, which are forcing many couples to pay a hefty amount for IVF (in vitro fertilisation) procedures.

Reliable irrigation is essential for maintaining yields under intensive cropping, as the new hybrid varieties cannot tolerate water shortage, and flood irrigation led to salinity and waterlogging problems in south-west Punjab (Narayanan, 2005). Similarly, excessive groundwater extraction is another effect. Where there is a depleting water table, more energy is required to lift water for irrigation. Farmers in India increasingly face constraints related to both water and energy. An increasing number of environmentally conscious consumers prefer food that does not affect their health and the environment. State-supported programs in developed countries like Sweden and Canada, and the example of a developing country like Indonesia, have exhibited that organic farming can reduce pesticide consumption by 50 to 65 per cent without surrendering crop productivity, along with 50 per cent less expenditure on chemical fertilisers and energy consumption (Pimentel et al., 2005).

Comparison of the economics of organic and conventional agriculture in the study areas reveals a complex picture. The yield of cereal crops has continued to be the same for the past many years, whereas the quantity of harmful chemicals has increased manifold. However, during the initial conversion period, the yield from the organic farm decreases by 15-20 per cent. Even then, profits are higher on an organic farm as the lower yield is balanced by lower input costs and higher economic returns.

The experiences of farmers in Turkey revealed that the conversion of conventional farms to organic farming initially resulted in a decline in productivity for approximately four to five years. However, after this transition period, crop yields gradually recovered and became nearly comparable to those achieved under conventional chemical farming. Similar observations were reported by an Indian organic farmer, who explained that the transition from chemical to organic farming is a gradual, step-by-step process. According to the farmer, newly converted organic farmers should not be discouraged by the temporary reduction in yields, as productivity improves over time with the restoration of soil health and ecological balance. Furthermore, farmers in both countries expressed concerns regarding the promotional and marketing practices of pesticide companies, which they believed often discouraged the adoption of organic farming by emphasising the immediate

benefits of chemical inputs while overlooking their long-term environmental and health impacts.

North Indian agricultural regions have experienced substantial pressure on soil and water resources due to the extensive use of fertilisers and pesticides. The Gramscian notion of 'crisis of authority' can be visualised as the cultivation of hybrid varieties resulted in a massive loss of aquifers in northwest India (Gramsci, 1999). Evidence suggests that more than five thousand litres of water are required to grow one kilogram of paddy in Punjab's geographical conditions. Even geospatial techniques strongly caution for the rapidly declining water table in north India (Rodell et al., 2009). Further, there is a continuous release of toxic chemicals from agriculture that contaminate the food and water (Brown, 2013). The activists of Kheti Virasat Mission in India and health authorities working in the Aegean region of Turkey expressed similar views that most of the toxic substances used these days have already been banned for use in agriculture in many developed countries. One can estimate the gravity of the problem by citing the example of the Malwa region in Punjab, which has emerged as 'Cancer Belt' on the world map. Malwa is a cultural-geographical region with less than 0.5 per cent of the area compared to the total geographical area of India, and the farmer fraternity here is spraying 75 per cent of the total pesticide consumption of Punjab (Mittal et al., 2014). The whole nightmare is propelled by the state in the name of food security. The so-called welfare state does not have any road map to save the subaltern agrarian society. It seems that the contemporary situation resembles the 'crisis of authority' in totality as the farming tradition is dying, and the alternative is not conceived (Brown, 2013; Gramsci, 1999). The health of the common man deteriorated because modern agricultural practices emphasised a few crops and utterly failed in providing a balanced diet. Before the Green Revolution, a farmer used to grow an average of 27 kinds of cereal, spices, herbs, vegetables, and fruits. After the advent of the Green Revolution, this number decreased to four or five products. The Green Revolution increased India's cereal production by many folds, but on the other hand, most small-scale farmers were trapped in debt. Their bodies are not strong enough to fight against weather change-related diseases and allergies. Capital-intensive agriculture has become increasingly difficult for small and marginal farmers to sustain profitably for small and marginal farmers, and even the medium-sized farmers have started joining the group of subalterns. The agrarian crisis has a clear class dimension, and hence the marginal farmers have three times more pressure of debt than large farmers, which directly results in the stress of indebtedness (Singh et al., 2008). David Harvey's concept of 'accumulation by dispossession,' the Green Revolution contributed to conditions that enabled neoliberal capitalist forces to control agricultural resources (Harvey, 2017). Further, the Green Revolution snatched the self-sufficiency of farming communities, and this helped the post-colonial state to continue with the hegemonic legacy with a minimum level of

resistance from the agrarian subalterns. Available accounts have documented very large numbers of farmer suicides after the advent of the Green Revolution in Punjab. Rural suicide remains a serious and continuing concern, which seems to be a reliable indicator of 'crisis of authority,' or the situation can be referred to as an organic crisis as conceptualised from Gramscian literature (Brown, 2013). Farmers' suicides are the alarm of the unfortunate aspect of the identity crisis for rural citizens of India's post-colonial state (Munster, 2012). During the post-economic reform times, the removal of farm subsidies and the casual approach of capitalist countries are happening as globalisation provides chances for cheap food imports (Lerche, 2011, 2013). According to Gramsci, the dominant class tries to create an environment of consensus, and the 'organic intellectuals' convince the subalterns of a change (Gramsci, 1999). Agricultural universities also face financial constraints and are dependent on MNCs for funding their research projects. Commercial pressures could influence research priorities to establish the hegemony of the elite section of society, and the private sector intrudes through their academic purists to capture the podium. Presently, the welfare state of both countries and their political elites are not capable enough to support the agrarian subalterns to cope with the hazard. Organic farming therefore emerges as one potentially viable pathway for the state and society, as the introduction of more imported models will lead to an epidemic and would end up in 'dying civilisation.'

In Turkey, many contemporary farming techniques conceived in the corporate offices and developed in the laboratories are introduced with limited consultation of farmers (farming community). The self-styled progressive farmers are importing modern practices on the recommendations of agricultural scientists who do not have much practical knowledge. The companies exhibit heuristic merits of the laboratory-tested formulas in contrast to the farm-tested methods over the generations. Hence, most of the imported methods failed, and the farming community is in distress. The field evidence reveals important dimensions of farmers' politics, changing political economy, and hegemony of food production in Turkey and India. The capitalist landlords engulfed the rural scenario after the failures of the green revolution during the decade of the nineties, and 'colonial hegemony' continues with the patronage of political elites that have profited from farmers' agitations and movements. The resistance to hegemony had a short-lived existence as neoliberalism gave birth to 'politics of negotiation' as a durable alternative to organised resistance. Organic food production in Turkey also has a strong corporate dimension in Turkey. The loss of self-sufficiency of the rural population resulted in a fragmented agrarian structure in which some segments of the society exercise hegemony over most of the farming community (Arora, 2001). Consequently, spatial injustice may deepen in the form of socio-spatial inequality, class-based tensions, loss of self-reliance and environmental injustice. The agrarian

subalterns are also experiencing the maximum burden of environment-related health loss.

Conclusion

The demand for organically produced food has grown substantially all over the world, encouraged by consumers' understanding that organic food is safe and healthy. Middle-class consumers are increasingly attentive to the nutrition and quality of food they eat. However, the development of organic agriculture remains strongly shaped by market forces, and this is the main reason that access to organic food is often concentrated among higher-income groups. The state has not always responded effectively in the critical situation; instead, of acting as an authoritarian state by executing domination by silencing the voice of the agrarian subalterns. Reduced state support has contributed to agrarian vulnerability, clearly in the form of suicides and health-related issues. Organic farming is based on circular causation theory and is an antidote to queries of human health, environment, agricultural sustainability, and above all, the failures of the Green Revolution. A carefully supported transition towards organic farming could help Turkey and India out of impending agricultural and environmental health crises to some extent. The central policy challenge for the state is how to provide financial help to boost the organic movement.

The longstanding relationship between the two countries provides a useful basis, and both nations must expand their cooperation while keeping in mind that they have a large rural population base and that promoting ecologically sustainable agriculture can contribute to rural development. Although Turkey ranks first in organic cotton production, the expansion of organic agriculture remains relatively gradual, and organic farmers currently focus on the cultivation of vegetables and fruits. Cereals are not much on the priority for farmers and the state. A major constraint is the price gap between organic and chemical food prices, and that is why more than 80 per cent of total production is exported to developed countries (Nardali and Gencler, 2011). India possesses a substantial base of producers and a growing consumer market with a variety of produce. Therefore, India has considerable potential to become a significant organic producer. Though the domestic consumer base is marginal and has concentrated in metropolises and cities, the upward trend is mainly the result of a nexus between the corporate sector and the elite section of society. It is the integration of the corporate-environmentalist food regime (Friedmann, 2005). Although several organizations have made important contributions in spearheading the organic movement. Organic farming can provide an important pathway to the contemporary issues of the rural population, mainly food sovereignty and environmental health. The right to produce food and the right to consume food ensure spatial justice.

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Role of Endophytes in Phytoremediation of Heavy Metals: Sustainable Agriculture

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Abstract

Heavy metal stress is also one of the most serious environmental stress which can occur through anthropogenic activities such as mining, smelting of metals, electroplating, gas exhaust, energy and fuel production, fertilizer, sewage and pesticide application, municipal waste generation increased the concentrations of heavy metals in the soils, significantly undermines crop productivity, food safety, and ecosystem health. The heavy metals such as Cd, Cu, Pb, Cr, Zn and Ni are the most common pollutants in the environment, form metal complexes in the soil which cause severe effects on plant life by means of cytotoxicity, mutagenicity and carcinogenicity inhibit the growth and yields of plants. The excessive concentration of these heavy metals significantly affects cellular organelles and damages the components of cell process, disturb the DNA, cell damage and repair functions and also other metabolic functions in the plants. Phytoremediation, a green and sustainable remediation strategy leveraging plants to extract, stabilize, or transform heavy metals in contaminated soils, has emerged as a promising alternative to conventional physiochemical approaches that are often costly, disruptive, and environmentally unsustainable. A new technique for cleaning up a variety of

organic and inorganic pollutants in the environment is based on plants and microbes. Phytoremediation, by means of plants, can remove soil pollutants without damaging the soil upper layers through processes that allow the stabilization, extraction or volatilization of heavy metals and xenobiotic compounds. Thus, Phytoremediation can provide innovative solutions to address the pressing challenges posed by climate change and environmental pollution for sustainable agriculture.

Keywords: Heavy metal stress, Carcinogenicity. Phytoremediation, Xenobiotic compounds.

Introduction

Heavy metal stress is also one of the most serious environmental stresses which can occurs through anthropogenic activities such as mining, smelting of metals, electroplating, gas exhaust, energy and fuel production, fertilizer, sewage and pesticide application, municipal waste generation etc. (Kabata Pendias and Pendias,1989). Excessive concentrations of heavy metals ions in the soil are highly absorbed by roots and translocated to shoot, leading to impaired metabolism and reduced growth (Bingham et al., 1986; Foy et al., 1978). The heavy metal toxicity through agricultural land by waste water irrigation has showed severe effect to the soil, plant and humans. Scientists confirmed that the heavy metals significantly inhibit the plant growth by reducing several physiological and biological functions especially photosynthesis, respiration, carbohydrate metabolism and water relation (Cunninghum and Ow, 1996; Saxena et al., 1999). Previous reports stated that the plant roots were absorbed the excessive concentrations of heavy metals which were translocated into shoot as results impaired metabolism and reduced growth (Bingham et al., 1986; Foy et al., 1978). The heavy metals such as Cd, Cu, Pb, Cr, Zn and Ni are the most common pollutants in the environment which cause severe effects on plant life by means of cytotoxicity, mutagenicity and carcinogenicity (Kanwal et al., 2018). The excessive concentration of these heavy metals significantly affects cellular organelles and damages the components of cell process, disturb the DNA, cell damage and repair functions and also other metabolic functions in the plants (Oves et al., 2013).Plants with a high iron content cause membrane damage and impair cellular structure by producing free radicals, DNA and proteins (Arora et al., 2002). Summarized that the severe impacts of heavy metal stress in crop plants included that low biomass accumulation, chlorosis, senescence, altered nutrient as well as water use efficiency, finally resulting plant death.

Although conventional physicochemical remediation technologies are very efficient, they are usually expensive, require a lot of energy, and cause environmental damage. The use of endophytic microbes is the most applicable and eco-friendly adaptive strategy for heavy metal remediation and resistance in plants

(Chen et al., 2015). Moreover, the endophytic microbes performed various detoxification methods includes immobilization, mobilization, absorption and transformation for heavy metal remediation (Hassan et al., 2017). Furthermore, the endophytic microbes have the efficacy to enhance plant growth, development and productivity by stimulating the production of growth regulators and efficient nutrient uptake during heavy metal stress (Nadeem et al., 2014; Tiwari et al., 2016). The use of microbial approaches for heavy metal tolerance and remediation is the most applicable and eco-friendly adaptive strategy. Bacteria are the most important microbial organisms employed in detoxification of heavy metals (Chen et al., 2015). (Hassan et al., 2017) described about the role endophytic bacteria in various detoxification methods of heavy metals like Immobilization, mobilization, absorption, transformation. Furthermore, various free-living and symbiotic PGPR dwells in the soil environment around plant roots, which can positively influence plant development and productivity by producing growth regulators and enabling efficient nutrient uptake from soil (Nadeem et al., 2014). Several studies have been published in which PGPR have been shown to be possible elicitors of abiotic stress tolerance, including heavy metal tolerance (Dary et al., 2010; Tiwari et al., 2016).

Phytoremediation-a green, in situ, and cost-effective strategy has gained popularity as a sustainable option for the treatment of contaminated soils (Malaviya et al., 2012; Rong et al.,2022; Xiong et al., 2025). The metal disturbs soil microbial communities, reducing nutrient cycling, enzymatic and microbial diversity, essentials oil fertility, and resilience factors. These microbial alterations reduce plant production and affect ecosystem function (Robinson et al., 2025). Phytoremediation, the employment of plants to immobilize or retrieve pollutants, is now a viable green technology used to solve various problems in metal and radionuclide pollution. Nevertheless, the effectiveness of phytoremediation in harsh mine tailings is typically hampered by inadequate plant establishment, diminished growth prompted by stress, and low contaminant transfer. One of the modern studies has pointed out that plant-microbe interactions, specifically endophytes, that is to say the part of a plant which can't be observed without using a microscope, significantly improve plant development, heavy metal intake, and abiotic stress tolerance, therefore remarkably facilitating phytoremediation. Endophytes offer stress resistance, and at the same time, they are involved in metal mobilization, metal sequestration, and metal biotransformation.

Plant associated endophytic bacteria plays a pivotal role in improving the efficiency of phytoremediation process. Plants and microorganisms have difficulty growing and settling under these conditions (Li et al., 2016; Gagnon et al., 2020). However, some native plant species interact with rhizosphere and endophytic microbial communities complexly, stabilize and accumulate the metals in their parts, and effectively handle these harsh conditions (Romero et al., 2021; Portman et al., 2023). Advances in metagenomics have helped us learn more about the diversity

and functional potential of microbes in metal-contaminated environments. Several research groups recently identified Rhizobiaceae, Burkholderiaceae, and Actinomycetia as key microbial taxa for metal detoxification and plant growth promotion. Majorly, these families consist of several metal detoxifying genes (such as chrR, acpD/azoR,arsR)that help in transport, solubilization, and detoxification of metals (Wang et al., 2022; Li et al., 2023). Some fungal communities are also associated with the rhizosphere, detoxifying the metals and ameliorating stress conditions. For instance, Ascomycota, which produce melanin, play a key role in mitigating stress in arid zones and minimizing the toxic effects of uranium (Poratman et al., 2023; Xiao et al., 2024).

The endophytic bacteria assured for detoxification and to remediate the pollutants from contaminated soil by hosting the plants without causing any damage symptoms and promotes plant growth and development by stimulating through several mechanisms such as nitrogen fixation, solubilization of minerals, production of phytohormones, siderophores, utilization of 1-aminocyclopropane-1-carboxylic acid and transformation of nutrient elements. PGPB have the efficacy to improve plant growth under heavy metal stress. The endophytic bacteria act as promising potential agents to develop tolerance towards heavy metal stress by phytoremediation process in plants. This phytoremediation contains several methods such as biotransformation, bioabsorption, bioaccumulation, biomineralization, biovolatilazation, bioleaching and biodegradation, which assist to alleviate heavy metal toxicity in plants (Karthik and Arulselvi, 2017). Moreover, the endophytic bacteria can assure to detoxify and remediate the heavy metal pollutants from contaminated soils by hosting into plants without causing any damage. The PGPB can excretes various metabolites such as exo-polysaccharides (EPS), hydrogencyanide (HCN), biosurfactants, antibiotic compounds and metal chelating agents which can reduced the plant stress caused by heavy metals. So, the endophytic bacteria act as potential tool in heavy metal phytoremediation processes (Burd et al., 2000; Rajkumar et al., 2010) (Table).

Table: Role of Heavy metal stress tolerance by Plant associated -micro-organisms

Endophytic bacteria/action-bacteria	**Host plant**	**Inoculated plants**	**Beneficial features related to Heavy metal tolerance**	**Citations**
Pseudomonas putida Bj05, *Pseudomonas fluorescens Ps14,*	*Switchgrass (Panicum virgatum L), seeds*	*Panicum virgatum L*	biomass and cadmium tolerance, lower bioavailability	*Afzal et al 2017*

Enterobacter spp. Le14, So02 and Bo03.			of Cd	
Burkholderia cenocepacia	*Populus deltoids marsh root and stems*	*Ralstoniam etallidurans*	high cadmium (Cd) resistance	*Wang et al 2019*
Piriformospora indica	*Rice seeds*	*Rice*	Arsenic tolerance, alleviate as phytotoxicity as biostimulant	*Ghorbani et al 2021*
Bacillusaryabhattai AS03 (MT645244) and Rhizobium pusense AS05	*Macrotyloma uniflorum var.*	*Macrotyloma uniflorum var. Madhu.*	alleviate Cr toxicity, Cr (VI)-tolerant nodule formation	*Shilpee Dhali et al 2021*
Enterobacter sp. MN17	*Brassica napus, rhizosphere*	*Brassica napus*	exopolysaccharides (EPS), siderophores, acidification and/or metal phosphates, cd tolerance	*Saeed et al, 2019*
Bacillus cereus WSE01	*Myriophyllumverticillatum stem*	*Myriophyllumverticillatum*	Fix the atmospheric nitrogen, Manganese tolerance	*Tang etal2020*
Pseudomonas and Sphingomonas	*Commelina communis Rhizosphere*	*Commelina communis*	enhance copper tolerance, phytoremediation	*Li He et al2021*

Proteobacteria, Actinobacteria. *Sphingomonadaceae*	*Sedum alfredii*	*Sedum alfredii*	Hyperaccumulator; Metagenome function	*Luo et al 2017*
B. koreensis 18122	*Rice roots*	***rice***	high Cd absorption capacity, admium resistance	*Zhou* *et al2021*
Buttiauxella sp. SaSR13	*Sedum alfredii, root*	*Sedum alfredii*	Cd phytoextraction efficiency	*Keren Wu* *et al, 2018*
Piriformospora indica	*Rice seeds*	*rice*	Arsenic tolerance, alleviate as phytotoxicity as biostimulant	*Ghorbani* *et al 2021*
Burkholderia *phytofirmansPsJN*	*mung bean (Vigna radiata)* *twigs*	*mung bean (Vigna radiata)*	Pb tolerance oxidative stres, antioxidant enzyme activities	*Naveed* *et al 2020*

Therefore, the endophytes, such as *Bacillus spp*. and *Pseudomonas spp*, improved the concentrations of metal accumulation and also tolerance to higher concentrations of heavy metals such as Cd, Pb, and U when inoculated into the non-host plants *Brassica napus* and *Helianthus annuus* (Anitha et al., 2023; Liu et al., 2024). These bacterial species produce siderophores and organic molecules that can interact with the mineral elements and heavy metals, making them more soluble and phytoavailable. Endophytes' assistance helps to uptake the metals, detoxify the metal ions, trapping them in extracellular capsules, which minimizes the phytotoxicity and stabilizes the re-entry of metals into the environment (Riseh et al., 2022; Tsotetsi et al., 2022; Wu et al., 2024).

Phytoremediation consists of numerous methods, including phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization. Among these,

phytoextraction and phytostabilization are especially important for the remediation of heavy metal contaminated soils (You et al., 2022; Ahmad, 2024).

However, these activities rely on the plant's capacity to absorb uranium from the rhizosphere and either transport it to aerial tissues or immobilize it within the root zone, decreasing its bioavailability and mobility (Reddy et al., 2019; Sharma, et al., 2023; Xiong et al., 2025). In the phytoextraction method, the plants take the metal from the soil and translocate it into the biomass (leaves). In the phytoremediation of uranium studies, hyperaccumulator plants such as *Brassica juncea, Helianthus annuus,* and *Lolium perenne* accumulated the uranium from the contaminated site and translocated it into the aerial parts. However, due to their low biomass, they are not useful for large-scale remediation of contaminated sites (Lone et al., 2008; Huang et al., 2022). These plants' roots generally secrete organic acids (citric, malic, and succinic acids) in the root exudates. As a result, these acids act as chelating agents, forming stable complexes with uranium ions U (VI), increasing the uranium solubility, decreasing the soil pH, mobilizing uranium from the soil, and enhancing the plant uptake capacity (Suzuki et al., 2007; Wang et al., 2021; Amesh et al., 2022). Some of the root-associated microorganisms, Arbuscular mycorrhizal fungi (AMF) and rhizobia bacteria, induce the phytochelatin synthase gene expression and detoxify the metal, improve the biomass of the plant, alter the root exudates, and improve the metal bioavailability (Ren et al., 2019).

The phytostabilization process curtails the contaminant in the rhizosphere, resulting in restricted contaminant metal mobility, which prevents the leaching of the metal into the groundwater. To remediate the uranium-contaminated soils, plant species such as *Salix spp*. and *Viburnum odoratissimum* have been used to stabilize the uranium contamination in the soil (Sha et al., 2019; Chen et al., 2021). The metal interacts with negatively charged molecules of the root, such as pectin, and compartmentalizes the metal into the vacuole to reduce the cytotoxicity. Sometimes the translocation factor genes are expressed at a low level in these plants to limit the translocation of the metals (Bakshe et al., 2023). In rhizofiltration, plant roots absorb metal from the contaminated water. Some aquatic plants will probably be used for this purpose. Plants such as *Eichhornia crassipes* and *Lemna minor* have been used for the rhizofiltration of uranium from the contaminated water (Pang et al., 2023).

The major limitation of phytoremediation is that it depends on the individual plant's stress tolerance, biomass, and metal degradation capabilities. Recently, several research groups have been exploiting the plant-associated microorganisms (Bacteria and Fungi) to overcome the drawbacks of phytoremediation. The symbiotic relationship between the plant and microorganisms improves the host plant biomass, breaks down the metals, and improves the stress tolerance of the host plants (Feng et al., 2017; He et al., 2020; Alves et al., 2022; Bhardwaj, 2025).

Plant roots secrete signalling molecules that attract rhizosphere soil microorganisms, which attach to the roots initially. Later, these microorganisms enter the inner tissue of the plants through their natural openings, such as root hairs and wounds (Rodrigo et al., 2013; Santoyo, 2022). Further, microorganisms suppress the plant's immunity system to establish themselves in the inner tissue of plants in a mutualistic manner and systematically alter the host metabolism, which helps the host plants grow, develop, and cope with stress. Endophytic microorganisms secrete catabolic enzymes such as hydrolases, lyases, and oxidoreductases that can convert toxic metals such as PAH (Polycyclic Aromatic Hydrocarbons), phenols and pesticides into a non-toxic form (Khan et al., 2017; Yang et al., 2024; Bhardwaj, 2025; Yang et al., 2025).

Recently, it was identified that endophytes adopt several mechanisms to detoxify metals, such as biosorption, methylation, bioleaching, and bioprecipitation, altogether to improve plant plasticity and phytoremediation efficacy of plants (Liu et al., 2024; Anita et al., 2023). The endophytic microorganisms also secrete low molecular weight molecules such as siderophores, which have a high affinity for Fe3+ and other heavy metals. They interact with the metals and alter the metal speciation, chelate the metal ions, and assist in the metal sequestration and bioavailability (Bhardwaj et al., 2025). Endophytes produce carboxyl groups of organic acids such as citric acid, malic acid, and oxalic acid, which interact with metal ions, convert them into non-toxic forms, and enhance their bioavailability (Osmolovskaya et al., 2018; Tiwari & Bae, 2023).

An efficient approach to improving the phytoremediation of heavy metals was to combine hyperaccumulator plants with endophytic bacteria. Several plant species and endophytic bacterial combinations were used for this purpose (Tiwari et al., 2023; Gamalero et al., 2024). Three endophytic bacterial species, "*Pantoea stewartii* ASI11, *Enterobacter sp*. HU38, and *Microbacterium arborescens* HU33" were inoculated into the *Leptochloa fusca*, individually and in consortia form, and plants were grown in U and Pb (200, 400, 1000mg/Kg-1) contaminated soil for a period of three months. Compared to the uninoculated plants, endophyte-inoculated plants exhibited improved growth (root and shoot) and phytoremediation. The BCF and TF factors of consortia inoculated plants were more than those of individual endophyte-inoculated plants (Ahsan et al., 2017). Arabidopsis plants inoculated with soil bacteria Microbacteria spViU2A and *Stenotrophomonas bentonitica* BH-R7 exhibited tolerance up to 100µM uranyl nitrate. Both of these bacteria help the plants to uptake the metal and detoxify the U toxicity (Galeone et al., 2024). A PGPR heavy metal-tolerant bacterial strain, *Bacillus cereus* B6 strain, improved the growth and biomass, uranium uptake capability of Sudan grass (Wu et al., 2025).

Conclusion

In conclusion, understanding the crucial role of endophytic halotolerant bacteria in mitigating the detrimental effects of abiotic stresses on plants is vital for developing sustainable and resilient agricultural practices in regions heavily impacted by these heavy metal stress. The use of endophytic microbes is the most applicable and eco-friendly adaptive strategy for heavy metal remediation and resistance in plants. Moreover, the endophytic microbes performed various detoxification methods includes immobilization, mobilization, absorption and transformation for heavy metal remediation. Harnessing the natural abilities of endophytes to thrive in heavy metal stress environments and leveraging the growth-promoting and stress-alleviating properties of endophytic halotolerant bacteria can provide innovative solutions to address the pressing challenges posed by climate change and environmental pollution in agricultural systems.

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Mathematical Models in Biology and Medicine

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Abstract

Mathematics is gradually becoming a critical companion to biomedical sciences by providing a language for formulating and validating scientific theories. In this paper, we seek to carry out an analysis of the various mathematical modelling techniques available for application in the disciplines of biology and medicine, especially those involving the spread of infectious diseases, population dynamics and the ways of analysis thereof. The classical SIR model will be analysed, and the basic reproductive number R_0 determined using the next-generation matrix technique. Moreover, models for diseases like Ebola virus disease, Nipah virus infection, and malaria will be explored. Local and global stability of equilibria are analysed using linearisation and Lyapunov functionals, and semi-analytical solution methods, in particular the Homotopy Perturbation Method (HPM) and its multistage variant (MHPM), are reviewed alongside standard numerical integration (fourth-order Runge–Kutta). A representative numerical simulation illustrates epidemic growth, peak prevalence, and the sensitivity of R_0 to the transmission and recovery parameters. The paper concludes by discussing the broader landscape of mathematical biology, including physiologically structured models, pharmacokinetic pharmacodynamic (PK/PD) models, and models of tumour growth, and by outlining open challenges for the field.

Keywords: mathematical biology; epidemic modelling; compartmental models; basic reproduction number; stability analysis; Homotopy Perturbation Method

Introduction

Mathematics for modelling biology and medicine has existed for more than two hundred years, from Daniel Bernoulli's study of the impact of smallpox inoculation in 1760 up to the current computerized era of epidemiology [1, 2].Mathematical models allow researchers to condense complex biological mechanisms into a small number of governing equations, generate quantitative predictions that can be tested against data, and evaluate the likely impact of interventions before they are deployed in practice [3,4]. In medicine, similar quantitative reasoning underlies pharmacokinetic dosing schedules, tumour growth models, and models of physiological regulation such as glucose–insulin dynamics [5].

The structure of this paper is as follows. The second section of this paper describes the main types of mathematical models that have been developed for use in biological sciences and medical applications. The third section elaborates on the concept of compartmental modelling in detail, involving model formation, basic reproductive number, and stability analysis. The fourth section gives a review of various analytical and numerical techniques for solving problems, which includes the Homotopy Perturbation Method. The fifth section illustrates a numerical case study.

Major Frameworks in Mathematical Biology

Mathematical models of biological and medical systems can be broadly classified into a few overlapping families, summarized in Table 1.

Principal classes of mathematical models used in biology and medicine.

Model class	**Typical formulation**	**Representative applications**
Compartmental (SIR/SEIR-type)	Systems of coupled nonlinear ordinary differential equations (ODEs)	Infectious disease spread (Ebola, Nipah, malaria, influenza) [2,4]
Population dynamics	Logistic, Lotka–Volterra, and age-structured equations	Predator–prey systems, cell population growth, demography [5]
Reaction–diffusion / spatial models	Partial differential equations (PDEs) with diffusion terms	Tumour invasion, wound healing, pattern formation [5]
Stochastic models	Markov chains, branching processes, stochastic differential	Small-population epidemic extinction, within-host viral

Model class	Typical formulation	Representative applications
	equations	dynamics [17]
Pharmacokinetic / pharmacodynamic (PK/PD)	Compartmental ODEs with dosing terms	Drug absorption, distribution, metabolism, and excretion [5]
Network / agent-based models	Graph-structured or individual-based simulations	Contact-network transmission, hospital infection control [4]

These include compartmental ODE models, which are still the most popularly applied modelling paradigm to study the epidemiology of infectious diseases due to their appealing combination of mathematical convenience and biologically plausible assumptions [6]. In what follows, we discuss this type of model.

Compartmental Epidemic Models

1. The SIR Model (Susceptible, Infectious, Recovered)

A population of size N is divided into three mutually exclusive compartments under the classical SIR model of Kermack and McKendrick [7]: susceptible S(t), infectious *I(t),* and recovered *R(t)* people, with *S(t)+I(t)+R(t)=N.* The dynamics are controlled by

$$\frac{dS}{dt} = -\frac{\beta SI}{N}, \quad (1)$$

$$\frac{dI}{dt} = \frac{\beta SI}{N} - \gamma I, \quad (2)$$

$$\frac{dR}{dt} = \gamma I, \quad (3)$$

where $\beta > 0$ is the effective transmission rate and $\gamma > 0$ is the recovery rate, so that $\frac{1}{\gamma}$ is the mean infectious period.

2. Extensions: Exposed, Hospitalised, and Vaccinated Classes

For diseases with a latent (non-infectious) period, such as Ebola virus disease and Nipah virus infection, an exposed class E(t) is introduced, yielding the SEIR model. Further refinements relevant to haemorrhagic fevers include a hospitalised compartment H(t), capturing isolation of confirmed cases, and a vaccinated compartment V(t), giving rise to SEIHRV-type models of the form

$$\frac{dS}{dt} = \Lambda - \frac{\beta SI}{N} - \nu S - \mu S, \quad (4)$$

$$\frac{dE}{dt} = \frac{\beta SI}{N} - (\sigma + \mu)E, \quad (5)$$

$$\frac{dI}{dt} = \sigma E - (\gamma + \delta + \eta + \mu)I, \quad (6)$$

$$\frac{dH}{dt} = \eta I - (\gamma_h + \delta_h + \mu)H, \quad (7)$$

$$\frac{dR}{dt} = \gamma I + \gamma_h H - \mu R, \quad (8)$$

$$\frac{dV}{dt} = \nu S - \omega V - \mu V, \quad (9)$$

where Λ is the recruitment rate, μ is the natural death rate, σ^{-1} is the mean incubation period, δ and δ_h are disease-induced death rates in the community and in hospital respectively, η is the hospitalisation rate, ν is the vaccination rate, and ω is the rate of waning vaccine-induced immunity [8,9]. Figure 1 depicts the compartmental flow structure of such a model.

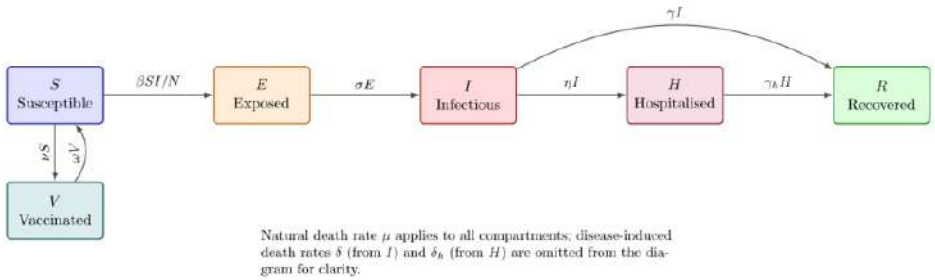


Figure1: Compartmental flow diagram for a generalised SEIHRV-type epidemic model, showing transitions between the susceptible (S), exposed (E), infectious (I), hospitalised (H), recovered (R), and vaccinated (V) classes.

3. The Basic Reproduction Number

The basic reproduction number, R_0, which represents the average number of secondary cases that can be caused by one infected person in a completely susceptible population, is the fundamental threshold parameter in epidemic modeling [10, 11]. Linearizing (10,11) at the disease-free equilibrium using the next-generation matrix approach, we obtain

$$R_0 = \frac{\beta}{\gamma}. \quad (10)$$

In general, for the disease transmission model where x denotes the infected compartments, $\dot{\boldsymbol{x}} = \boldsymbol{F}(\boldsymbol{x}) - \boldsymbol{V}(\boldsymbol{x})$ where F is composed of new infection terms and V consists of transfer terms $\boldsymbol{R_0 \rho}\left(\boldsymbol{F V^{-1}}\right)$, the spectral radius of the next-generation matrix at the disease-free equilibrium [11]. The epidemic threshold theorem states

that the disease-free equilibrium is locally asymptotically stable whenever $\boldsymbol{R_0 < 1}$ and unstable whenever $\boldsymbol{R_0 > 1}$ [11].

4. Stability Analysis

Local stability of equilibria is assessed via the Jacobian of the system evaluated at the equilibrium point; all eigenvalues having negative real part implies local asymptotic stability by the Hartman–Grobman theorem [12]. Global stability is typically established using a Lyapunov functional $\mathcal{L}$ satisfying $\mathcal{L} \geq 0$ with equality only at the equilibrium, and $\dot{\mathcal{L}} \leq 0$ along trajectories. For the endemic equilibrium of SEIR-type models, functionals of the Volterra–Goh type,

$$\mathcal{L} = \sum_k c_k \left(x_k - x_k^* - \frac{x_k^* \ln x_k}{x_k^*} \right), \tag{11}$$

with suitably chosen constants c_k , are commonly used to prove global asymptotic stability of the endemic equilibrium when $R_0 > 1$ 1 [13].

5. Sensitivity Analysis

Because β, γ, and other parameters are typically estimated from imperfect surveillance data, it is important to quantify how sensitive R_0 is to each parameter. The definition of the normalized forward sensitivity index of R_0 in relation to a parameter p is

$$\Upsilon_p^{R_0} = \frac{\partial R_0}{\partial p} \cdot \frac{p}{R_0}. \tag{12}$$

For the simple relation (10), $\Upsilon_\beta^{R_0} = +1$ and $\Upsilon_\gamma^{R_0} = -1$, indicating that R_0 responds proportionally, and in opposite directions, to changes in the transmission and recovery rates.

Analytical and Numerical Solution Methods

1. The Homotopy Perturbation Method

Because the governing equations of compartmental models are nonlinear and generally lack closed-form solutions, semi-analytical techniques are used to obtain approximate series solutions. The Homotopy Perturbation Method (HPM), introduced by He [14,15], embeds a homotopy parameter $p \in [0,1]$ into the governing equation

$$H(u,p) = (1-p)[L(u) - L(u_0)] + p[N(u) - f(r)] = 0, \tag{13}$$

where L is a linear operator, N a nonlinear operator, and u_0 an initial approximation. Expanding $u = \sum_{n=0}^{\infty} p^n u_n$ and collecting terms of equal powers of p yields a recursive sequence of linear problems for $u_0, u_1, u_2, \ldots$, whose sum (at p=1) approximates the true solution.

2. Multistage HPM

Standard HPM series solutions are often only accurate over short time intervals because they are effectively Taylor-type expansions about t=0. The Multistage Homotopy Perturbation Method (MHPM) addresses this limitation by partitioning the time domain $[0,T]$ into subintervals $[t_k, t_{k+1}]$ of width τ, applying HPM on each subinterval, and using the terminal values of one subinterval as the initial condition for the next [16]. This piecewise reapplication substantially extends the interval of validity while retaining a semi-analytical closed form on each subinterval, and is particularly effective for stiff epidemic systems evaluated over multi-month simulation horizons.

3. Numerical Validation

Semi-analytical HPM/MHPM solutions are routinely validated against direct numerical integration using the classical fourth-order Runge–Kutta (RK4) method,

$$y_{n+1} = y_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4), \qquad (14)$$

with $k_1 = f(t_n, y_n)$, $k_2 = f(t_n + h/2\,, y_n + h/2\,k_1)$, $k_3 = f(t_n + h/2\,, y_n + h/2\,k_2)$, and $k_4 = f(t_n + h, y_n + hk_3)$ [18]. Close agreement between MHPM and RK4 solutions across the simulation horizon is generally taken as evidence of the accuracy of the semi-analytical approximation.

Numerical Case Study

To illustrate the theoretical framework of Section 3, we numerically integrate the SIR model (1)-(3) with representative parameter values $\beta = 0.30\ "day"^{-1}$ and $\gamma = 0.10\ "day"^{-1}$, giving $R_0 = 3.0$ from Eq. (10), a value consistent with reported Ebola outbreak estimates [9], using an initial condition of 1% initial prevalence in an otherwise susceptible population. Figure 2 shows the resulting epidemic curve.

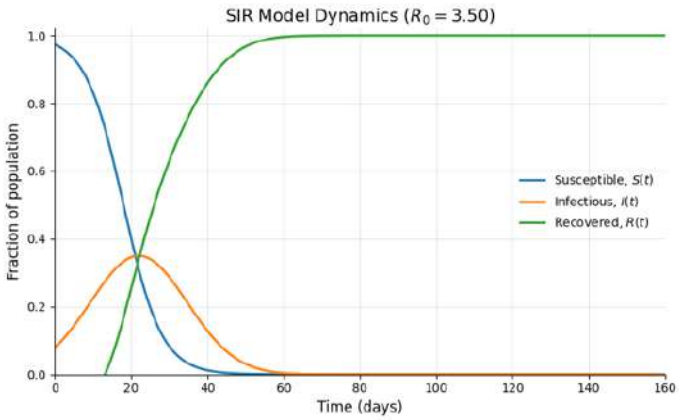


Figure2: Simulated SIR epidemic dynamics with $\beta = 0.30\ "day"^{-1}$, $\gamma = 0.10\ "day"^{-1}$ $R_0 = 3.0$. The infectious fraction peaks at approximately 30% of the population near day 27, consistent with the threshold behavior predicted by Eq. (10).

Table 2 summarises the parameters used in the simulation together with typical literature ranges for the diseases discussed in Section 3.

Table 2: Illustrative epidemiological parameters and literature-reported ranges.

Parameter	Description	Simulation value	Reported range
β	Transmission rate (day^{-1})	0.30	0.10–0.60 [9]
γ	Recovery rate (day^{-1})	0.10	0.07–0.20 [8]
R_0	Basic reproduction number	3.00	1.5–4.0 [9]
$\frac{1}{\gamma}$	Mean infectious period (days)	10.0	5–15 [8]

Figure 3 illustrates the sensitivity of R_0 to β across several values of γ, in accordance with the sensitivity index derived in Eq. (12): for fixed γ, R_0 grows linearly with β, and lower values of γ (longer infectious periods) shift the entire curve upward, widening the region in which R_0 exceeds the epidemic threshold of unity [11]. This pattern is consistent with reported outbreak dynamics for haemorrhagic fevers, where prolonged infectious periods in the absence of isolation measures have been associated with sustained epidemic growth [8].

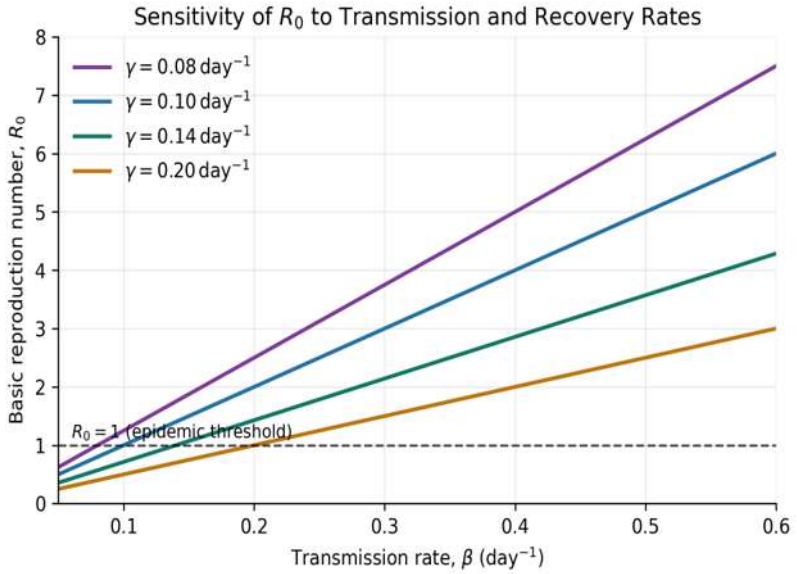


Figure 3: Sensitivity of the basic reproduction number $\mathbf{R_0 = \frac{\beta}{\gamma}}$ to the transmission rate β, plotted for four representative values of the recovery rate γ. The horizontal dashed line marks the epidemic threshold $\mathbf{R_0 = 1}$

Discussion

This type of model, as discussed above, also generalises to more complicated situations. Reaction-diffusion models in space address the spread of disease and

invasion of tumours in space. stochastic models become necessary in cases where the populations are sufficiently small such that demography alone can cause the extinction of an outbreak even if $R_0 > 1$; and network models take into account contact structures that are important for healthcare-acquired infections. In medical applications, similar compartmental models also play a role in pharmacokinetics and physiological feedbacks like glucose-insulin regulation.

One of the problems that arise when using any of these models is the problem of parameter identifiability since there are several parameters related to epidemiology and physiology which cannot be determined independently of the data which is provided. Another problem that emerges is the problem of combining the deterministic nature of MHPM and similar solutions with the inherent stochastic nature of the outbreak during its initial stage.

Conclusion

The present review has provided an overview of the various mathematical approaches adopted to construct mathematical models for biological and medical systems, with special emphasis on compartmental epidemic models, basic reproduction number, stability analysis, and semi-analytical techniques like the Homotopy Perturbation Method and its multistage form. A typical SIR model was used to demonstrate the threshold dynamics determined by R_0. The further development of combined deterministic and stochastic modelling techniques, along with the accurate determination of their parameters through epidemiological and medical data, is the key to the future of mathematical modelling in public health and medicine.

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Survey and Documentation of Aromatic Plants in Mata Jija Bai Govt. P.G. College Campus Indore M.P.

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Abstract

The present communication deals with the treasure of aromatic plants in India and Madhya Pradesh. In Madhya Pradesh Indore is a one of the well-known commercial capitals. The business of medicinal and aromatic plants very huge. The findings in present communication shed light on the availability and potentiality of aromatic plants in India as well as in Madhya Pradesh. In Indore Mata Jija bai Government post graduate college Indore is rich in biodiversity specially in medicinal and aromatic plants. The study deals with the aromatic plants survey reports. According to survey during one year tenure from July 2024 to June 2025. The survey report and documentation of aromatic plants are belonging to -26 -family -31 -species. From which dicot plants are --24--and monocot plants are. --5 reported.in survey report. the conclusion is that the college campus rich in biodiversity of medicinal plants and aromatic plants. These plants need conservation, protection and maintenance by college authority.

Keywords: Fragrance, Aromatic Plants, survey report.

Introduction

Aromatic plants are peculiar and different from other plants by their fragrance pleasant smell. the aromatic plants have essential oil contents. Essential oils are secondary metabolites presents in oil glands. except secondary metabolites carbohydrates, phenols, alcohols, ethers, aldehydes and ketones are present in oil glands. The oil glands may be presents in leaves, stem, flowers, barks, and other parts of plants. (Joshi 2013) India has rich in biodiversity of medicinal plants,

aromatic plants their use and conservation supported by socio-cultural practices such as worship of plants, plantation.

Aromatic Plants have been used in medicine perfumery, fragrance for thousand s of year (Abu-Rubia 2005) During last few decades there has been an increasing interest in the study of medicinal and aromatic plants and their traditional uses and in the development of fragrance for different uses in cosmetics, perfumery, Bakary items.

Material and Methods

During survey in college campus, we have collected aromatic plants for perfumery purposes in order to adapt aroma identification by using physical methods, such as squeezing plant parts and inhaling through the nose and used to cure various ailments. Because the nostrils of the human nose contain a number of factory receptor neurons that function as sensory signalling cells to detect odours. Personal interviews were used to collect all of the plants, and the information gathered was recorded in a field note book. Taking photographs in the field and creating a digital herbarium with floras (Gamble and Fischer, 1915-1935).

Aromatic plants, since antiquity, have been employed to flavour food and drinks, to impart fragrance to human body, to beautify homes, for religious rites and personal adornment, in cosmetics and medicine, as incense and insect repellent, etc. Aromatic plants are vegetation that produce volatile organic compounds, mainly essential oils, which create distinct and pleasing scents. Key families like Lamiaceae, Poaceae, and Asteraceae are heavily researched for extracting oils used in medicine, cosmetics, and sustainable environmental clean-up

Observation Table

S.No.	Name of Plants	Family	Vernacular Name	Life form
1.	*Allium Cepa L.*	Liliacaeae	onion	Herb
2.	*Aegle marmolus*	Rutaceae	Bel	shrub
3.	*Alistonia scholaris L.*	Apocynaceae	Saptparni	tree
4.	*Aloevera L.*	Liliacaeae	Guavrpatha	herb
5.	*Annona Squamosa L.*	Annonaceae	Seetaphal	shrub
6.	*Aspergus racemousus L.*	Liliacaeae	Satvari	Climber

7.	*Azadihrcta indica*	Meliaceae	Neem	Tree
8.	*Bahunia verigata*	Ceasalpineace	Kachnar	Tree
9.	*Centella asiatica*	Apiaceae		
10.	*Citrus aurantifolia*	Rutaceae	Nimbu	Shrub
11.	*Clerodendron inerme G.*	Verbeneaceae		Shrub
12.	*Coriandrum sativum L.*	Apiaceae	Dhniya	Herb
13.	*Curcuma longa L.*	Zinzeberaceae	Haldi	Herb
14.	*Cyperus rotundus L.*	Cyperaceae	Nagarmotha	Herb
15.	*Cestrum nocturnum*	Solanaceae	Ratrani	Shrub
16.	*Eucalyptus globulus*	Myrataceae	Nilgiri	Tree
17	*Jasminum officinale L.*	Oleaceae	jasmin	shrub
18	*Lawsonia inermis*	Lythyraceae	Mehndi	Shurb
19	*Callistomon lanceolatus*	Myrtaceae	Bottle brush	Tree
19	*Murrya paniculeta*	Rutaceae	Orange Jasmine	shrub
20	*Michelia champaca L.*	Magnoliaceae	Champa	Shrub
21	*Moringa olefera L.*	Moringaceae	Sahjan	Tree
22	*Murrya Koenigii*	Rutaceae	Kadi Patta	Shrub
23	*Nyctanthus arbor-tristis L.*	Oleaceae	Harsingar	Shrub
24	*Ocimum basilium L.*	Lamiaceae	Tulsi	Herb
25	*Rosa damascena M.*	Rosaceae	Gulab	Herb

26	*Santalum* al*bum L.*	Santalaceae	Chandan	Tree
27	*Tagetus erecta L.*	Asteraceae	Ganda	Herb
28	*Punica granatum L*	Punicaceae	Anar	Shrub
29	*Citrus maxima L.*	Rutaceae	santra	shrub
30.	*Nycatanthes arbor-tritis*	Oleaceae	Har singar	Shrub
31	*Cymbopogon citratus*	Poaceae	Lemon grass	Herb

Result and Discussion

The fragrant plants can be use by human being for different uese like cosmetics, confectionary perfumes, itre and deo industry. The aromatic plants also used by Ladies in hair decoration Champa, (*Michelia campca*,) Jasmin Turmeric (*curcuma longa*) for skin tonning, sandal (*santalum album*) wood for fragrance. Mehndi (*Lawsonia inermis*) for colouring conditioner *Emblica officinalis* (awala) (citrus medica) lemon for Vitamin C.

The survey during July 2024 to July 2025. 31 Angiospermic plants reported from college campus. The 5 plants belonging to monocotyledons and 24 plants belonging to Dicotyledonous plants. The monocot families are Liliaceae, Cyperaceae and Poaceae.

Aromatic plants usually have fragrance due to presence of essential oils in different plants parts They probably act as attracting insect for pollination or feeding animals. They are also known as ethereal oil. They are volatile in nature. The primary source of aromatic plants in terms of different species. The highest number of monocot plants belonging to family Liliaceae (3) Poaceae, Zinzeberaceae, Cyperaceae have single family. In dicot family the Rutaceae (4) Myrtaceae (2) and others family have single genera represent the family.

The fragrant plants can be use by human being for different uese like cosmetics, confectionary perfumes, itre and deo industry. The aromatic plants also used by Ladies in hair decoration Champa, *Michelia campca*, Jasmin Turmeric (*curcuma longa*) for skin tonning, sandal (*santalum album*) wood for fragrance. Mehndi (*Lawsonia inermis*) for colouring conditioner *Emblica officinalis* (awala) (citrus medica) lemon for Vitamin C.

Conclusion

In Recent decades, the world-wide uses of aromatic plants increase as evidenced by the growing number of products in the pharmaceutical, cosmetics, chemical, food

and related industries. The aromatic oil is used for fragrance in perfume industries, confectionary bakery and other purposes.

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Biomass as a Sustainable Energy Source: Resources, Conversion Technologies and Future Prospects

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Abstract

The increasing global demand for clean, renewable, and sustainable energy has intensified interest in biomass as an alternative to fossil fuels. Biomass represents one of the most abundant and versatile renewable energy resources, derived from agricultural residues, forestry waste, animal manure, municipal solid waste, algae, and dedicated energy crops. As a carbon-based renewable resource, biomass plays a significant role in reducing greenhouse gas emissions, enhancing energy security, promoting waste management, and supporting rural economic development. This chapter provides a comprehensive overview of biomass as a sustainable energy source by examining its diverse feedstock resources, characteristics, and availability. It discusses the major biomass conversion technologies, including thermochemical processes (combustion, gasification, pyrolysis, and liquefaction), biochemical processes (anaerobic digestion and fermentation), and physicochemical methods for biofuel production. The chapter also explores the production and applications of bioenergy in the form of heat, electricity, biogas, bioethanol, biodiesel, bio hydrogen, and advanced biofuels. Furthermore, environmental, economic, and social aspects of biomass utilization are critically evaluated; highlighting both the opportunities and challenges associated with sustainable biomass production, feedstock logistics, technological limitations, land-use concerns, and policy frameworks. Recent advancements in integrated bio refineries, circular bio economy concepts, carbon capture technologies, and artificial intelligence-assisted biomass management are discussed as emerging approaches to improve biomass conversion efficiency and sustainability. Finally, the chapter outlines future prospects and strategic recommendations for expanding biomass utilization as a key component of the global transition toward low-carbon and

sustainable energy systems. By integrating technological innovations with supportive policies and sustainable resource management, biomass has the potential to become a major pillar of future renewable energy portfolios and contribute significantly to achieving global climate and sustainable development goals.

Keywords: Biomass; Bioenergy; Thermochemical Conversion; Biochemical Conversion; Gasification; Pyrolysis; Sustainable Development.

Introduction

The rapid growth of the global population, industrialization, urbanization, and rising energy demand have placed unprecedented pressure on conventional fossil fuel resources. Fossil fuels, including coal, petroleum, and natural gas, currently account for the majority of global energy consumption; however, their continued use has resulted in significant environmental challenges such as greenhouse gas (GHG) emissions, climate change, air pollution, and ecosystem degradation. The increasing awareness of these environmental impacts, coupled with concerns over energy security and the depletion of non-renewable resources, has accelerated the global transition toward renewable and sustainable energy systems. Among the various renewable energy sources available today, biomass has emerged as one of the most promising alternatives due to its widespread availability, versatility, and potential to provide carbon-neutral energy.

Biomass refers to biodegradable organic material derived from plants, animals, microorganisms, and organic wastes. It includes agricultural residues, forestry residues, livestock manure, municipal solid waste, food waste, sewage sludge, algae, and dedicated energy crops. Unlike intermittent renewable energy sources such as solar and wind, biomass can be stored and utilized continuously, making it a reliable and dispatch able source of energy. Through appropriate conversion technologies, biomass can be transformed into heat, electricity, liquid biofuels, gaseous fuels, and a variety of value-added bio products that contribute to a sustainable bio economy.

The utilization of biomass for energy production has a long history, dating back to the use of firewood for cooking and heating. However, recent technological advancements have significantly expanded its applications. Modern biomass conversion technologies include thermochemical processes such as combustion, gasification, pyrolysis, and hydrothermal liquefaction; biochemical processes including anaerobic digestion and fermentation; and physicochemical processes for biodiesel production through trans esterification. These technologies enable the efficient conversion of biomass into renewable fuels such as bioethanol, biodiesel, biogas, syngas, bio-oil, bio hydrogen, and renewable electricity. Continuous improvements in process efficiency, feedstock utilization, and emission control have enhanced the commercial viability and environmental sustainability of biomass-based energy systems.

One of the major advantages of biomass is its contribution to climate change mitigation. Since the carbon dioxide released during biomass combustion is largely balanced by the carbon absorbed during plant growth through photosynthesis, sustainably managed biomass is often considered a low-carbon or carbon-neutral energy source. Furthermore, biomass utilization supports the circular economy by converting agricultural, industrial, and municipal wastes into useful energy, thereby reducing landfill disposal, methane emissions, and environmental pollution. The integration of biomass into waste management strategies also promotes resource efficiency and sustainable development.

Biomass energy offers significant socioeconomic benefits, particularly in rural and developing regions. The cultivation of energy crops, collection of agricultural residues, biomass processing, transportation, and bioenergy production generate employment opportunities and provide additional income for farming communities. Decentralized biomass-based energy systems improve access to modern energy in remote areas, reduce dependence on imported fossil fuels, and strengthen national energy security. Moreover, biomass contributes to several United Nations Sustainable Development Goals (SDGs), particularly affordable and clean energy (SDG 7), climate action (SDG 13), responsible consumption and production (SDG 12), and sustainable cities and communities (SDG 11).

Despite its considerable potential, biomass energy development faces several challenges. Sustainable biomass production requires careful management to avoid competition with food production, deforestation, biodiversity loss, excessive water consumption, and land-use change. Feedstock collection, transportation, seasonal availability, storage, and supply chain logistics also influence the economic feasibility of biomass-based energy systems. In addition, some conversion technologies require substantial capital investment, technical expertise, and supportive policy frameworks to achieve large-scale commercialization. Environmental concerns related to particulate emissions, ash disposal, and life-cycle greenhouse gas emissions must also be addressed to maximize sustainability.

Recent innovations are transforming the biomass sector and improving its future prospects. The development of integrated bio refineries enables the simultaneous production of biofuels, bioenergy, chemicals, fertilizers, and biomaterials from a single feedstock, thereby enhancing resource efficiency and economic viability. Advanced technologies such as artificial intelligence, machine learning, remote sensing, precision agriculture, and Internet of Things (IOT) -based monitoring are increasingly being applied to optimize biomass production, supply chain management, and conversion efficiency. Furthermore, coupling biomass energy systems with carbon capture, utilization, and storage (BECCS) offers the potential for negative carbon emissions, making biomass an important component of global climate change mitigation strategies. This chapter provides a comprehensive overview of biomass as a sustainable energy source by discussing its major

feedstock resources, classification, physicochemical characteristics, and global availability. It critically examines the principal biomass conversion technologies, including thermochemical, biochemical, and physicochemical processes, highlighting their advantages, limitations, and commercial applications. The chapter also evaluates the environmental, economic, and social dimensions of biomass utilization, recent technological developments, policy initiatives, and future research directions. By integrating scientific knowledge, technological advancements, and sustainability considerations, this chapter aims to provide readers with a thorough understanding of the role of biomass in supporting the global transition toward a low-carbon, resilient, and sustainable energy future.

Energy Sources from Biomass

Green plants are natural solar collectors that convert solar energy into chemical energy as plant matter. Wood and other plant materials are therefore forms of solar energy. Since coal and oil are formed from plant matter, they are also forms of solar energy. Yet while wood is considered a renewable energy source, coal and oil are considered non-renewable energy sources, coal and oil are considered non-renewable. The difference has to do with the time required for coal and oil to form literally millions of years. In terms of energy the important things going on during these millions of years are that chemical energy is being considered. Terrestrial plants have a mean energy content of about 5 kWh per kilogram of dry weight; petroleum products have the equivalent of slightly less than 12 kWh per kilogram (Björk and Graneli, 1978); coal has the equivalent of about 9 kWh per kilogram. All of this suggests a strategy of using plant mass or biomass as energy. The trade-off involved would be using fuel with a lower energy content (having more weight to handle) in exchange for its being renewable and available relatively immediately. Far from being a new idea, biomass has been used as fuel for centuries, its most familiar form being firewood. In some places, biomass as firewood is still heavily exploited today. In fact, it is probably fair to say that most human beings in the world still rely on biomass for their energy needs. According to D. Hayes (1977) and many others, biomass directly derived from photosynthesis may have a significant role to play in providing energy on a worldwide basis in the future. There have been various proposals, some involving the deliberate cultivation of plants to be used for fuel (energy farming) and some involving the use of waste or scrap biomass.

A proposal for the use of the common reed as fuel and a description of some of the spin-off benefits of large-scale reed cultivation for the purpose of generating energy are given by Björk and Graneli (1978). Various other common and troublesome plants have been discussed as possibilities; some of these include the water hyacinth and certain varieties of algae (Hayes, 1977). There are still other sources of biomass. Perhaps the most advantageous source is waste in municipal refuse and

agricultural and forestry residues. Pimentel et al. (1981) claim that residues after forest and agricultural crop production amount to nearly one-fifth of the total U.S. biomass production, with a gross heat energy equivalent of 12% of the fuel consumed annually in the United States. One fifth of this is potentially harvestable and usable, but this is still equivalent to a significant fraction of dedicated energy consumption.

1. Alcohols from Biomass

Biomass can be burned directly, or it can be converted to other forms of fuel. Two related examples of liquid fuels derivable from biomass are methanol (CH_3OH) (wood alcohol) and ethanol (CH_3CH_2OH) (grain alcohol). The nice thing about methanol is that it can be made from almost any kind of existing fuel. It can be made from fossil fuels as well as from a number of forms of biomass ranging from wood harvested especially for conversion to the cellulose-based scrap in municipal, agricultural, and forestry wastes Ethanol is produced in other forms of bioconversion, just as yeast makes ethanol from grape juice, a variety of anaerobic microbes, including yeast, can make ethanol from sugar or other carbon compounds. Many of us have used this energy product in gasohol, a mixture of gasoline and ethanol.

2. Natural Gas

Methane can be generated from animal waste such as cow manure. The methane (CH_4) produced in this way can be used in the same way as natural gas. According to one estimate, if all manure produced in the United States every year by our cattle and hogs were used to produce this kind of energy, it could provide 5% of our total gas consumption. Of course, there is no way that all manure could be used for this purpose. In theory, it would take about 30 head of cattle to supply the heat needs of an average household. Sewage and other wastes can also be fermented to yield usable gas.

3. Petroleum from Plants

Certain shrubs have sap containing hydrocarbons similar to those found in petroleum. Calvin (1979) claims to have demonstrated the economic feasibility of producing oil from hydrocarbon-producing species of the genus Euphorbia. These plants are especially appealing because they grow in semiarid areas and thus are not in competition with food crops. The concept of “petroleum from plants” refers broadly to the production of liquid hydrocarbon fuels, bio-oils, and petroleum substitutes from plant biomass. Unlike conventional petroleum, plant-derived fuels are produced from recently fixed biological carbon. Plants capture atmospheric carbon dioxide through photosynthesis and store it as carbohydrates, lipids, proteins and other organic compounds. These compounds can subsequently be converted into fuels through biochemical, thermochemical and catalytic processes. Plant

biomass includes agricultural residues, forestry residues, dedicated energy crops, oilseed crops, algae and other lignocellulosic materials. Depending on the feedstock and conversion technology, biomass can be transformed into bio-oil, biodiesel, renewable diesel, sustainable aviation fuel, gasoline-range hydrocarbons and petrochemical intermediates. Technologies such as pyrolysis, hydrothermal liquefaction, gasification followed by Fischer–Tropsch synthesis, fermentation and catalytic upgrading are particularly important in this context (Bridgwater, 2012; Wang et al., 2013). The conversion of plants into petroleum substitutes generally involves three major stages:

Plant biomass → Primary conversion → Upgrading/refining → Liquid fuels and chemicals

Pyrolysis: Pyrolysis involves the thermal decomposition of biomass in the absence or near absence of oxygen. Depending on the operating conditions, pyrolysis produces bio-oil, bio char and non-condensable gases. Fast pyrolysis is particularly important for producing liquid bio-oil. However, raw bio-oil generally contains substantial oxygen, water and reactive compounds and therefore has properties different from conventional petroleum. Catalytic upgrading, hydrodeoxygenation and other refining processes can improve its stability and fuel quality (Bridgwater, 2012).

4. Energy Balances for Biomass Conversion

It takes energy to grow biomass. In the conversion of biomass deliberately grown for energy production to ethanol for gasohol, for example, a key question is: Can more energy be obtained than is put in in the forms of fertilizer, pesticides, and gasoline. Chambers et al. (1979) concluded that if conventional agricultural techniques and conventional. Distillation techniques are used, the net energy balance for gasohol production is negative more energy has to be put in than is obtained out. They acknowledge that with some generous assumptions concerning energy-efficient agricultural practices and using crop residues there could be a modestly positive energy balance. They also acknowledge that if the goal is to produce fuel that can substitute for petroleum and if more plentiful fuels such as coal provide the energy to produce alcohol, energy from biomass might not be a bad idea. Even with this, however, gasohol turns out to be a rather inefficient method of converting coal to liquid fuel.

DaSilva et al. (1978) report "very favourable energy balances" for the conversion of sugar cane and sorghum to alcohol. They emphasize the importance of evaluating specific crops individually. Calvin (1979) points out that sugar cane is one of the world's most efficient converters of solar energy into chemical energy and indicates that sugar cane can be converted to alcohol with very little net energy loss. He drives home his point by describing a sugar plantation as a completely energy self-

sufficient system. The waste remaining after sugar juice is extracted can be burned, yielding more than enough steam to generate all the electricity needed to run the sugar mill and the fermentation process and to generate the fertilizer required for sugar cane production.

Advantages, Problems, and Disadvantages with Biomass as Fuel

Several advantages are commonly cited in using biomass for energy. For one thing, some of the starting materials already exist, unused, in some cases amounting to waste disposal problems. The clear advantage is that biomass is a renewable energy source. Neither the use of waste biomass nor the use of biomass derived from energy farms is without problems and limitations, however.

Pimentel et al. (1978) conclude that the potential for biomass conversion from waste and energy farming is quite limited. Acknowledging that the total harvest of agricultural and forestry products amounts to 5.8×10^{15} kcal of net energy (equal to 32% of our fossil fuel consumption), Pimentel and colleagues (1984) report that biomass-derived energy currently amounts to only 3% of the total energy consumption in the United States. However, they project that biomass could provide about 11% of gross U.S. energy by the year 2000.The production of biomass materials to be used as sources of gaseous and liquid forms of energy raises many important questions relative to the environment. The large amounts of land needed would raise many land-use questions, not the least significant of which would be: Should land now used for food production, in a world short of food, be used to grow "energy" in a world short of energy. The use of marginal or otherwise currently unused lands would bring with it various environmental problems such as habitat destruction and erosion. Energy farms will tend to produce the same kinds of environmental problems found in other types of agricultural or forestry production, namely, erosion, ecosystem simplification, ecosystem disruption, and fertilizer runoff. Collecting, transporting, processing, and ultimately burning biomass will generate air pollution and other pollution problems as well (Pimentel et al., 1984).

Consequences

In summary, it can be said that both biomasses produced for fuel and biomass wastes can be converted into easily handled fuels such as methane, methanol, ethanol, and even powders. While this is an interesting possibility, one that might provide some fraction of our energy needs in the future, the potential of this source is not yet known. There have as yet been no large-scale tests of such energy systems that would indicate cost and technical difficulty. Energy farming would have much the same environmental impact as food farming and forestry, and there may well be environmental impacts yet to be discovered. One of the most promising future directions is the conversion of crop residues, animal manure, and food-processing waste, municipal organic waste and forestry residues into useful energy. Such

approaches can simultaneously address waste-management problems and reduce dependence on fossil fuels.

Agricultural residues such as rice straw, wheat straw, maize residues, sugarcane bagasse and animal manure can be converted into biogas, bio methane, biofuels, pellets, producer gas and electricity. This approach is particularly relevant to developing countries because locally available biomass can support rural energy supply and generate additional income for farmers. FAO emphasizes that sustainable bioenergy from agricultural and other organic residues can contribute to energy security, rural development, and employment and climate objectives. Biomass is expected to have an increasingly important role in sectors where complete electrification is technically or economically difficult. These include aviation, shipping, heavy industry, high-temperature industrial processes and some chemical industries. The International Energy Agency projects continued growth in renewable fuels through 2030, with bioenergy accounting for the large majority of this growth. The projected role of biomass in future energy systems is substantial, although it will depend on sustainability constraints and technological progress. IRENA's 1.5°C pathway projects that modern bioenergy could provide 22% of total primary energy by 2050, requiring biomass supply to increase substantially from 2020 levels.

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Bioremediation Strategy in AMR Polluted Environment

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Abstract

The increase in population at an alarming rate has led to increase in urbanization, industrialisation and agriculturalization which in turn has led to an increase in several types of pollution. This is usually bolstered up by industrial waste discharges, agricultural runoff containing fertilizers and pesticides, untreated domestic sewage, oil spills, and the dumping of non-biodegradable plastics into oceans and rivers. The health of the living world is on the edge of a thin ice. This creates an indispensable need for a remedy, although there are a diverse array of remedies using physical & chemical methods, however, due to setbacks associated with them have fostered the use of an alternative which is bioremediation. Bioremediation refers to the use of microorganisms to eliminate or reduce the concentrations of hazardous wastes at a contaminated site (Boopathy, 2000; de Lorenzo, 2008). Antibiotic contamination is an ever more dire problem due to the massive usage of antibiotics, removal complexity, and detrimental impacts on the environment. AMR is a natural evolutionary process enhanced by human actions. When microbes are exposed to antimicrobial drugs (such as antibiotics), the weakest ones die. However, a small fraction of microbes with random genetic mutations may survive. These survivors increase in number, pass on their resistant DNA to the next generation, and also to other microbes. In this regard genetically modified microbes were produced to degrade and eliminate antibiotics such as tetracyclines and other (Microbial Mol Biol Rev. 2001 Jun;65(2): 232260.doi: 10.1128/MMBR.65.2.232-260.2001). CRISPR-Cas mechanism made possible to

cut the targeted antibiotic resistance genes which are present on either plasmid or host chromosomes. (https://doi.org/10.1016/j.medmic.2026.100173).

Keywords: Microbial resistance, Bioremediation, Genetic engineering microbes, CRISPR Cas9 technique.

Introduction

Overview of Antimicrobial Resistance (AMR) As an Environmental Contaminant

Antimicrobial resistance is a hazardous Environmental contaminant which poses a serious problem when raw materials such as unused drugs, medicines, drug resistant germs and bacteria enter the ambience and makes it a hub for breeding creating untreatable Supergerms.

Sources of antibiotic pollution (pharmaceutical runoff, agriculture, hospital waste)

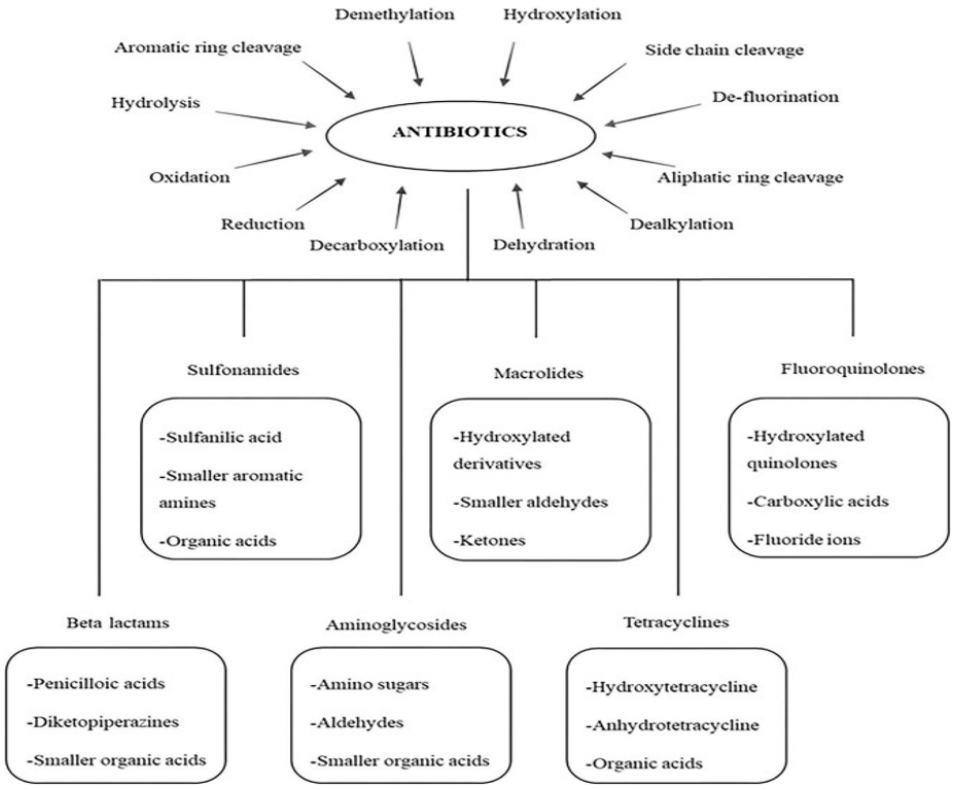
Pisciculture is a mega industry globally and the usage of antibiotics is more prevalent to minimise the infections in fishes and to have more yield. The most commonly used antibiotics include oxytetracycline, florefenicol, sarafloxacin etc. In apiculture, antibiotics like Oxytetracycline are used to inhibit bacterial infection of larval stages of bees. However, honeybees cannot metabolize these substances, and oxytetracycline is found to be present at very high levels in honey (Meek et al. 2015). As preservatives, antibiotics like streptomycin are used in apple and pear orchards to protect from fire blight infection. Antibiotics are also added during fermentation process in ethanol manufacturing sector to inhibit bacterial infections.

Effluents from home include excretion of antibiotics by humans, unused personal care products and outdated medicines are flushed in the toilets. Many common domestic products like shampoo, soap, or children's toys contain antibacterial agent, Triclosan. Resistance genes for quaternary ammonium compounds (QACs) have also been identified and studied in many bacterial strains; thereby increasing concerns on the prevalent use of these QACs in a variety of common personal care and domestic products Hospital wastes like discarding the antibiotics, leftover medicines and patients excreta when left untreated ,will further escalate the AMR problem.

Leftover pharmaceuticals enter into water and land ecosystems through human and animal waste, hospital and industry discharges, and inadequate waste management practices. These pollutants present severe ecological dangers and mark a crossing of the Rubicon in the rise and spread of antimicrobial resistance (AMR), posing an irreversible threat to both the environment and public health.

Mechanisms of Biological Degradation

The biological degradation of antibiotics involves the breakdown using various biological agents which includes microbes such as bacteria, fungi, algae and their metabolites (enzymes and proteins) (Chandel et al., 2022) During this process less toxic byproducts are obtained with no chemical's usage, thereby also prevents the problem of chemical sludge. Antibiotic compounds, bacterial resistant genes and other organic matters can be degraded by mechanisms such as demethylation, hydroxylation, side chain cleavage, defluorination, aliphatic ring cleavage, dealkylation, dehydration, decarboxylation, reduction, oxidation, hydrolysis and aromatic ring cleavage leading to production of respective by-products (Kireeva et al., 2021; Navada and Kulal, 2019).



Degradation Mechanism of Broad-Spectrum Antibiotics and Their Possible By-Product
Image source : https://pmc.ncbi.nlm.nih.gov/articles/PMC13095611/figure/F7/

The bioaugmentation process includes the introduction of targeted microorganisms capable of efficiently degrading targeted antibiotics.This methodology is widely applied in composting, where aerobic microbial activity can accelerate antibiotic removal while simultaneously sanitising manure. Sphingobacterium changzhouense TC931, isolated from farm manure, achieved tetracycline removal rates of 58% on day 2 and 87% on day 3, primarily through biosorption via extracellular polymeric substances and enzymatic biodegradation.

Bioremediation Strategies

1. Phytoremediation of Antibiotics

Phytoremediation approach utilizes the implementation of hyper accumulator plants to absorb, degrade, or stabilize antibiotics from the environment. This approach encompasses various techniques, such as phytoextraction, phytodegradation, rhizofiltration, phytostabilization, phytostimulation, phytotransformation, and phytovolatilization (Zhou et al., 2024). Key studies include the capacity of sunflower (Helianthus annuus) to absorb a wide range of antibiotics, particularly tetracycline and sulfamethoxazole, from contaminated soil has also been reported (Conde-Cid et al., 2020).

2. Biodegradation of Antibiotics by Bacterial Enzymes

Bacterial enzymes tend to bind with the ring structure of the antibiotics in turn leading to the cleavage of the ring structure or nullify the effects of antibiotics. Bacteria produce enzymes of vital importance that acts as unfailing remedy for antibiotics bioremediation which include aminoglycoside modifying enzymes and antibiotic-modifying enzymes (Luthra et al., 2018), macrolide esterases (Nicoloff and Andersson, 2016) and tetracycline inactivating enzyme that chemically alters and neutralizes their activity (Reis et al., 2020).

Genetically Modified Microbes and Its Applications In AMR

Due to unavoidable various activities of human approaches antimicrobial resistance (AMR) emerged as a global environmental challenge. Antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs) are released into the environment majorly because of mismanagement of hospital effluents, Wastewater treatment plants and also increased use of antibiotics ((Bai et al. 2017; Power et al. 2018; Wang 2018). Most of the microorganisms has become resistant to antibiotics which makes even the most potent drugs ineffective (Sabiha Nusrat et.al). Hence this led to a challenge in treating a routine infection, medical procedures such as surgery and chemotherapy.

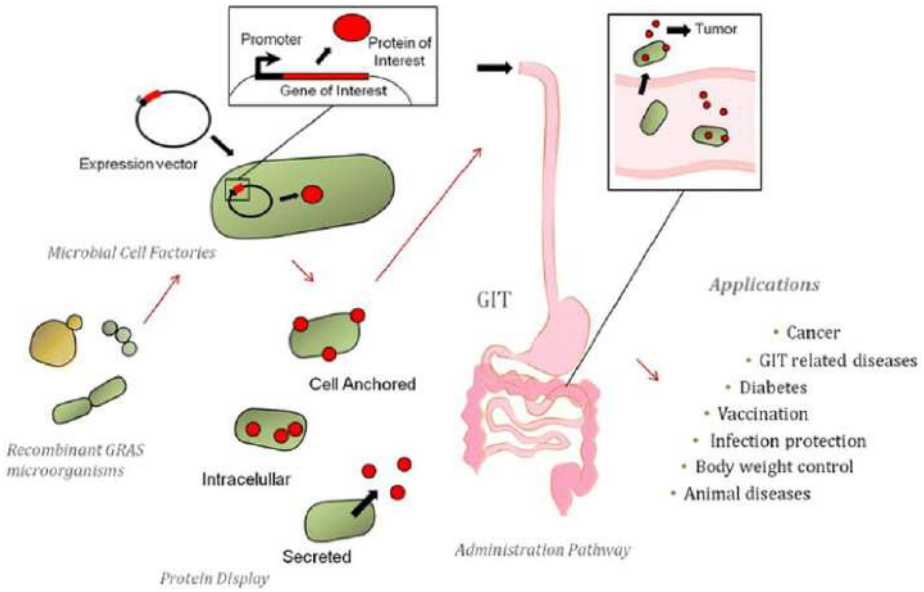
In this regard customized bacteriophages are employed in personalized treatment (Debmitra Sen, Poulami Mukhopadhyay). Use of bacteriophages in the treatment of diseases caused by the antimicrobial resistant organisms became an effective alternative for antibiotics.

Anand Chakraborthy developed a Superbug to degrade oil spill from the sea. Pseudomonas putida was genetically transformed with plasmids derived from four different bacteria containing naphthalene, octane, camphor and xylene degrading plasmids to make it into a superbug.

By genetic engineering techniques, extremophiles have acquired special features which enabled them to use in bioremediation processes. (Wang et al., 2022).

Genetically edited thermophiles has the potential to high temperature and are used in bioremediation of waste heat-environments (Eggers et al., 2024).

Genetically modified Lactobacillus have probiotic properties which enabled them to undergo expression of wide range of antigens that promotes the immune system (Md. Rayhan Chowdhury et.al).



Lactic acid bacteria: reviewing the potential of a promising delivery live vector for biomedical purposes. Image Source: Spring Nature.

CRISPR Cas gene editing technique

1. Mechanism

This is a technique of bacterial (Streptococcus pyogenes) immune system where the phage DNA is degraded so that virus is neutralized (Jennifer A Doudna, Emmanuelle Charpentier et al) . After infection, a section of phage DNA is incorporated into the bacterial genome between the repeated palindromic sequences (spacer).

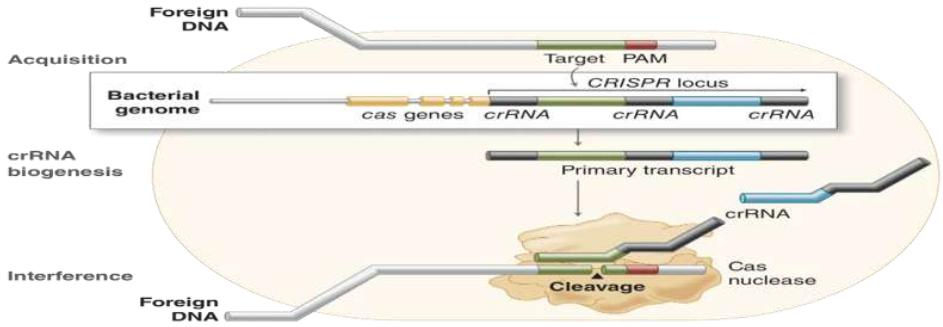


Image source: https://www.neb.com/en/tools-and-resources/feature-articles/crispr-cas9-and-targeted-genome-editing

The CRISPR array undergoes transcription process to form pre CRISPR-RNA (pre-Cr-RNA).

The CRISPR associated nuclease protein called Cas9 i9s capable of cleaving DNA. It acts as a molecular scissor (Misganaw Asmamaw , Belay Zawdie 2021 Aug 21;15:353–361). Pre-Cr RNA, tracer RNA and Cas 9 proteins forms a complex called Effector complex. With this effector complexes the cell is ready to defend against the invading viruses. If these complexes encounters a section of viral DNA, that has a sequence which is complimentary to this Cr RNA the nuclease enzyme will co-ordinate and it recognizes the short sequence PAM(Proto spacer Adjacent Motif) and cuts the DNA upstream to PAM. By cutting the DNA, it neutralizes the virus because its genome cannot undergo transcription process to make more viral particles. This process explains CRISPR in prokaryotes as a natural defense.

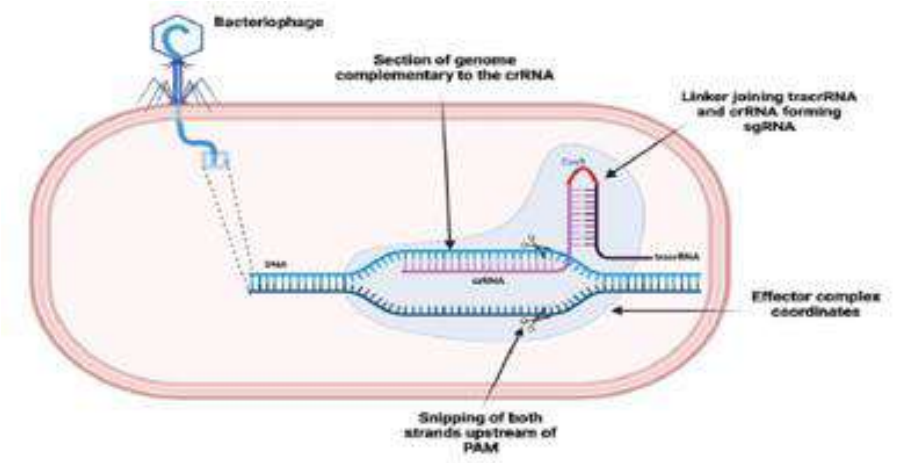


Image source: DOI:10.7759/cureus.64324

2. CRISPR Cas gene editing in AMR

The major application of this technique is used in genetic engineering to make a cut in the targeted site in DNA. Antimicrobial resistant genes can be cut by using this molecular scissor mechanism and make the antibiotic-resistant bacteria into antibiotic sensitive organisms (Mohamed Mustaf Ahmed, Hassan Hakeem Kayode et al).

- CRISPR Cas mechanism employed to remove colistin resistance genes in MCR 1 plasmid and hence bacteria such as E. coli and Klebsiella pneumoniae has become sensitive to carbapenems like Meropenem, Imipenem etc.
- CRISPR Variation mechanism is used in altering the resistant genes and can reduce its resistant capability. tetM and ermB antibiotic genes of E. faecalis are successfully made sensitive or less resistant to tetracycline and erythromycin antibiotics.

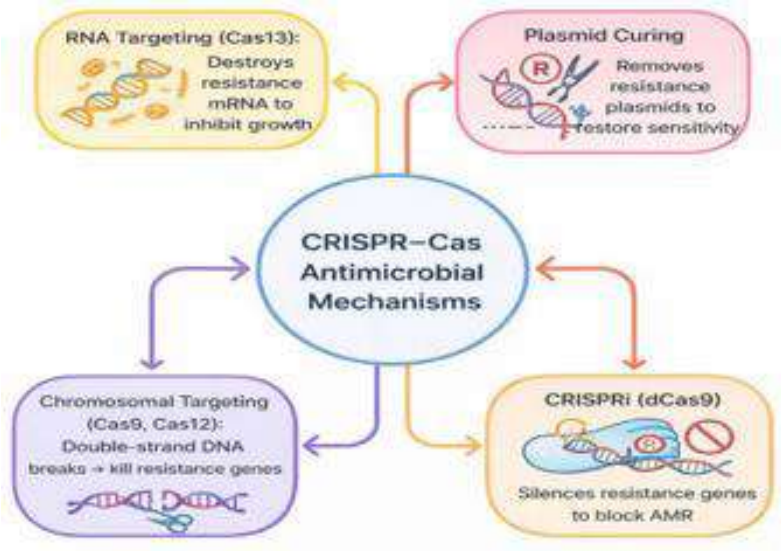


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- Double strand breaks can be done in plasmids which carry antibiotic resistant genes by CRISPR mechanism and bacteria can be made sensitive to antibiotics. Antibiotic resistant plasmids like bla, mcr-1 are removed and antibiotic susceptibility restored in the microbes.
- Bacterial growth can be inhibited by silencing the resistant genes without cutting the DNA by CRISPR dCas9 mechanism (Maha S. I. Wizrah 11 May 2026).

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