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Medicinal and Aromatic Plants in Sustainable Agriculture: An Integrative Review of Bioactive Applications and Future Directions

Snigdharani Dash*

Department of Biotechnology and Bioinformatics, Sambalpur University, Jyoti Vihar, Burla, Sambalpur, India

**Corresponding author*

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A B S T R A C T

The projected global population growth to 9.7 billion by the year 2050 poses a critical challenge to global food security, requiring approximately a 70% increase in agricultural output. This demand is further intensified by the shrinking availability of cultivable land, escalating impacts of climate change, increasing incidence of plant pathogens and pests and the global shift towards eco-friendly and sustainable farming practices. In this context, there is an urgent need to explore innovative and natural strategies to enhance crop productivity without compromising environmental and consumer safety. One promising approach involves the application of bio-based agricultural inputs such as bio-fertilizers, bio-pesticides, and bio-stimulants derived from plant sources. Medicinal and aromatic plants (MAPs) have gained considerable attention due to their rich phytochemical profiles, including alkaloids, essential oils, glycosides, polyphenols, quinones, steroids, and terpenoids. These naturally occurring compounds are being explored for their potential to improve plant growth, enhance stress tolerance, and reduce dependence on synthetic agrochemicals. This review focuses on the role of MAP-derived plant extracts in promoting sustainable agriculture and summarizes current advancements, highlighting their prospective applications as green alternatives in crop management practices.

Introduction

The global population is anticipated to reach approximately 9.7 billion by the year 2050, marking a 19% increase from present figures. To meet the nutritional demands of this expanding population, the Food and Agriculture Organization (FAO) has estimated a required rise of nearly 70% in overall food production. However, this ambitious goal is challenged by several limiting factors, including the scarcity of cultivable land, increased pest and pathogen pressure, and various abiotic stresses such as drought, temperature extremes, irregular rainfall, soil salinity, and fluctuating light intensity (Molotoks *et al.*, 2018). These constraints pose significant threats to both the quantity and quality of agricultural produce.

Since the onset of the Green Revolution in the 1960s, chemical fertilizers and pesticides have played a pivotal role in boosting agricultural productivity (Pingali, 2012).

While these agrochemicals have delivered considerable benefits in terms of yield improvement, their excessive and prolonged use has led to negative environmental consequences, including soil degradation, water contamination, and biodiversity loss (Ogunnupebi *et al*., 2020; Jacquet *et al*., 2022). Moreover, increasing awareness of food safety and environmental sustainability has led to rising public concern over chemical residues in food products and their long-term impact on ecosystems and human health.

In recent years, a global transition towards sustainable agriculture has been gaining momentum. Driven by both consumer demand and policy interventions, many countries are now actively encouraging environmentally friendly farming practices. For instance, the European Union has introduced the Green Deal and the Farm to Fork Strategy, aiming to reduce the usage of hazardous pesticides by 50%, chemical fertilizers by 20%, and to increase organic farming to 25% by the year 2030.

Similar policy frameworks are being adopted in countries such as India and the United States. Despite these advancements, the implementation of harmonized global standards for sustainable agriculture remains a complex challenge due to regional differences in regulations and resources (Jacquet *et al*., 2022).

To support this shift towards sustainability, there is a growing emphasis on the development and application of biological alternatives to synthetic agrochemicals. This includes biofertilizers, biostimulants, and biopesticides, which not only enhance crop productivity but also contribute to environmental conservation. Biofertilizers are formulated using beneficial microorganisms or natural substances that promote plant growth by increasing nutrient availability. Biostimulants, as defined by EU Regulation 2019/1009, are products that improve nutrient uptake, stress tolerance, and crop quality, independent of their nutrient content. Biopesticides are derived from natural sources such as plants, microorganisms, or minerals, and are used to manage agricultural pests and diseases without the harmful side effects associated with chemical pesticides (Ogunnupebi *et al*., 2020). Among the promising sources of bioactive agricultural inputs are medicinal and aromatic plants (MAPs), which have been traditionally utilized for their therapeutic and aromatic properties.

These plants are known to produce a wide array of phytochemicals, including alkaloids, glycosides, polyphenols, flavonoids, terpenoids, and essential oils, many of which possess antimicrobial, antifungal, antioxidant, and plant-growth-promoting properties (Dash and Pattnaik, 2024, 2025; Fierascu *et al*., 2021; Godlewska *et al*., 2021).

Globally, out of an estimated 4,22,000 plant species, approximately 50,000 to 80,000 are used for medicinal and aromatic purposes, including herbaceous species, shrubs, and trees (Chen *et al*., 2016; Suna *et al*., 2019; Pergola *et al*., 2024).

Technological advancements in the field of phytochemical analysis—such as chromatography, mass spectrometry (MS), UV–Vis spectroscopy, and Fourier-transform infrared (FTIR) spectroscopy—have greatly facilitated the isolation and characterization of bioactive compounds from MAPs. These innovations have not only improved our understanding of the functional roles of these compounds but have also accelerated the development of novel bio-formulations aimed at enhancing agricultural productivity and resilience (Ahmad Dar *et al*., 2020; Mabasa *et al*., 2021).

Despite the progress, further research is needed to comprehensively evaluate the efficacy of plant-based extracts in managing biotic and abiotic stresses in crops. Notably, traditional botanical insecticides, such as extracts from garlic (*Allium sativum*) and nettle (*Urtica dioica*), have shown effectiveness in managing insect pests in native agricultural systems (González-Macedo *et al*., 2023). Recent studies also emphasize the untapped potential of plant-derived natural products in drug development, agricultural innovation, and sustainable farming solutions (Chaachouay and Zidane, 2024).

This review seeks to provide an in-depth overview of current scientific knowledge on the agricultural potential of medicinal and aromatic plant extracts, with a particular focus on herbaceous plants, small perennials, and shrubs. By compiling and analyzing recent findings, this work aims to highlight the role of MAPs in supporting the transition toward more sustainable and eco-friendly agricultural practices.

Chemical Composition of Medicinal and Aromatic Plants

Medicinal and aromatic plants (MAPs) are rich reservoirs of bioactive secondary metabolites, which are synthesized as part of their natural defence mechanisms and physiological functions. These secondary metabolites, including alkaloids, glycosides, phenolics, quinones, steroids, and terpenoids, exhibit a broad range of biological activities that contribute to plant resilience and offer potential applications in agriculture as biostimulants, biopesticides, and growth enhancers (Teoh, 2015; Alseekh and Fernie, 2023).

Alkaloids, a diverse group of nitrogen-containing compounds, are known for their roles in plant defence and therapeutic properties (Waller and Nowacki, 1978; Dey *et al*., 2020). Their structural diversity and biological potency make them significant in crop protection and plant health (Lichman, 2021; Heinrich *et al*., 2021). Glycosides, comprising sugar and non-sugar moieties, play critical roles in stress signalling and growth modulation and are now recognized for their utility as plant-based therapeutics (Kytidou *et al*., 2020). Essential oils and their constituents, such as monoterpenes and sesquiterpenes, possess strong antimicrobial and antioxidant properties and are widely applied as natural pesticides and preservatives (Dhifi *et al*., 2016; Bolouri *et al*., 2022; Chrysargyris *et al*., 2024). Polyphenols, another important group, act as antioxidants and signaling molecules, contributing to enhanced plant defense and tolerance to abiotic stress (Kisiriko *et al*., 2021; Ortiz and Sansinenea, 2023). Quinones, derived from aromatic compounds, are involved in plant respiration and oxidative signaling and have demonstrated plant growth regulation potential (Ranade and David, 1985; Nowicka *et al*., 2021; Monks and Jones, 2002). Steroids, particularly phytosterols and brassinosteroids, influence various physiological responses such as fruit development, stress mitigation, and yield improvement (Bishop and Yokota, 2001; Vriet *et al*., 2012; Fenn and Giovannoni, 2021; Du *et al*., 2022). Similarly, terpenoids, among the largest classes of plant metabolites, are known for their diverse ecological roles and industrial applications, ranging from pharmaceuticals to eco-friendly pesticides (Ninkuu *et al*., 2021; Fan *et al*., 2023). These compounds, due to their structural variety and multifunctionality, serve as the biochemical basis for many plant-derived formulations used in sustainable agriculture.

Biocidal Potential of Medicinal and Aromatic Plants

According to the Food and Agriculture Organization (FAO), approximately 20–40% of global agricultural production is lost annually due to pests, diseases, and weeds, with nearly 67,000 species of organisms adversely affecting cultivated lands each year (Tavares *et al*., 2021). Pesticides are crucial for crop protection against a variety of harmful organisms such as bacteria, fungi, insects, mites, weeds, nematodes, mollusks, and rodents. However, as previously discussed, the intensive application of synthetic pesticides raises environmental and human health concerns (Aioub *et al*., 2024). For instance, endosulfan, a persistent organochlorine compound formerly used as an insecticide and acaricide, has been banned in many countries due to its bioaccumulation and neurotoxicity (Ghosh *et al*., 2018). Similarly, carbofuran, another widely used pesticide, was banned across the European Union in 2008 due to its severe neurotoxic effects on non-target organisms including mammals, birds, and aquatic species (Kamboj *et al*., 2006).

To mitigate such issues, there is a growing emphasis on replacing hazardous chemical pesticides with eco-friendly alternatives. Biopesticides derived from medicinal and aromatic plants offer a promising substitute, as they are biodegradable and exert minimal environmental impact (Chandler *et al*., 2011). Nevertheless, these biological products often face regulatory challenges because existing guidelines are tailored to synthetic pesticides, leading to high development costs and prolonged approval timelines, particularly in resource-constrained regions.

Crop pests vary widely, requiring diversified biocidal mechanisms. Acaricides may function as repellents, oviposition deterrents, or lethal agents at various developmental stages. Fungicides can inhibit spore germination, mycelial proliferation, or reduce infection severity. Bactericides act by disrupting bacterial cell membranes or walls, impeding cell division (Meng *et al*., 2024), inhibiting biofilm formation (Husain *et al*., 2017), or affecting signal transduction pathways (Vikram *et al*., 2010). Insecticidal activities may involve oviposition deterrence, larval growth disruption, feeding inhibition, or direct toxicity. Nematicides often interfere with egg hatching, while rodenticides and molluscicides exert their effects through antifeedant actions and induced toxicity (Malhotra *et al*., 2023).

Medicinal and aromatic plant extracts demonstrate significant biocidal efficacy against agricultural pests and pathogens. Despite promising in vitro results, detailed investigations are necessary to isolate active constituents, elucidate modes of action, and validate field performance to ensure practical applicability.

Bioherbicidal Potential of Medicinal and Aromatic Plants

Weeds pose a serious constraint in agricultural productivity by competing with crops for vital resources such as nutrients, water, light, and space. Additionally, they may serve as alternate hosts for a variety of pests and pathogens (Hasan *et al*., 2021). Such competition can lead to substantial crop yield losses, with estimates suggesting a reduction of up to 31.5% in some farming systems (Kubiak *et al*., 2022). To combat this, synthetic herbicides have been extensively used as a primary weed control method. However, the long-term use of these chemicals has drawn criticism due to their detrimental impacts on both the environment and human health (Mohd Ghazi *et al*., 2023).

For instance, paraquat—a widely used non-selective herbicide—has been banned in many countries due to its high toxicity profile. As a potent oxidizing agent, paraquat induces severe oxidative stress and cellular damage in both animals and humans (Gao *et al*., 2020). These concerns have accelerated the search for environmentally safer alternatives, including plant-based bioherbicides. These biological agents derive their efficacy from natural phytotoxic compounds, known as allelochemicals, which inhibit the germination and growth of neighboring plant species (Abd-ElGawad *et al*., 2020; Khamare *et al*., 2022).

Bioherbicides sourced from medicinal and aromatic plants (MAPs) typically exhibit reduced environmental persistence and lower toxicity, making them attractive components of sustainable weed management programs (Hasan *et al*., 2021). However, it is essential to recognize that these natural compounds are not entirely risk-free. Their application must be managed carefully to avoid adverse effects on non-target crops and beneficial organisms.

Several allelochemicals exhibit specific mechanisms that suppress weed growth. For example, eugenol disrupts seed germination, while camphor affects photosynthesis and respiration processes. Thymol interferes with chromosomal alignment during cell division, quercetin disturbs hormonal regulation, and menthone enhances membrane permeability leading to cell death. Other compounds like α-pinene are known to induce oxidative stress and restrict nutrient uptake (Singh *et al*., 2006).

Despite the growing body of evidence supporting the herbicidal potential of MAP extracts and their constituents, there remain significant gaps in understanding the exact biochemical pathways and modes of action they target. Additionally, optimizing the mode of application—whether pre- or post-emergence—and understanding their selective efficacy against monocotyledonous or dicotyledonous weeds are areas requiring further investigation. Such insights are crucial for the formulation of reliable and effective bioherbicidal products that can complement or replace synthetic herbicides in modern agriculture.

Oxidative Stress–Reducing Effects of Medicinal and Aromatic Plants

Most agricultural land faces a range of biotic and abiotic stresses that can significantly affect crop productivity. Biotic stresses include pests, diseases, and weed competition, while abiotic stresses encompass drought, temperature extremes, salinity, and nutrient deficiencies, among others (Biswas and Das, 2024). Plants inherently produce small amounts of reactive oxygen species (ROS) as byproducts of regular metabolic processes such as cellular respiration and photosynthesis. Under optimal conditions, these ROS are efficiently neutralized by the plant's internal antioxidant systems. However, under stress, ROS levels can accumulate beyond manageable limits, initiating oxidative damage cascades. This results in lipid peroxidation, protein oxidation, compromised membrane integrity, DNA damage, and eventually cell death (Sachdev *et al*., 2021).

Mitigating ROS accumulation is, therefore, crucial for reducing oxidative stress under adverse environmental conditions. Medicinal and aromatic plants (MAPs) are renowned for their antioxidant properties, largely due to their phytochemical constituents. These include compounds that neutralize both radical and non-radical reactive species.

For instance, anthocyanins and coumarins effectively scavenge free radicals, thereby protecting critical biomolecules like DNA, proteins, and lipids from oxidative injury (Blando *et al*., 2018). Flavonoids such as quercetin can chelate transition metal ions (e.g., $Fe2^{+}$, $Fe3^{+}$, and $Cu2^{+}$) that catalyze the generation of ROS via Fenton-type reactions (Leopoldini *et al*., 2006).

Other compounds, such as rosmarinic acid, are known to enhance antioxidant defenses by upregulating both the expression and activity of antioxidant enzymes like Superoxide Dismutase (SOD), Catalase (CAT), and Glutathione Peroxidase (GPX) (Zhu *et al*., 2021).

Furthermore, molecules like ascorbic acid (vitamin C) and glutathione not only scavenge ROS but also regenerate other antioxidants, thereby sustaining the redox homeostasis within plant cells (Gallie, 2013; Hasanuzzaman *et al*., 2017).

Although numerous studies emphasize the antioxidant capabilities of MAPs, limited research has focused on their direct role in alleviating oxidative stress in crop plants under field conditions. Further investigations are warranted to harness their full potential in sustainable agriculture.

Biostimulant Effects of Medicinal and Aromatic Plants

As defined under the Fertilizing Product Regulation (EU) 2019/1009, biostimulants are substances or microorganisms that stimulate plant nutrition processes, independent of the product's nutrient content, with the sole aim of improving one or more of the following characteristics of the plant: nutrient use efficiency, tolerance to abiotic stress, quality traits, or availability of nutrients confined in the soil or rhizosphere. These agents help mitigate oxidative damage and nutritional stress, leading to improved plant development and productivity.

Biostimulants operate through three primary nutrient-use efficiency mechanisms: (i) increasing nutrient availability in the soil solution or on exchangeable colloids, (ii) improving the absorption and transport of nutrients by the root system, and (iii) facilitating the assimilation and internal utilization of nutrients in plant metabolism. This results in enhanced crop performance even with reduced fertilizer input. Furthermore, by increasing nutrient mobility from soil particles or air-filled pores into plant-accessible forms, they ensure better nutrient uptake.

Regarding abiotic stress, biostimulants improve plant resilience against adverse environmental conditions such as heat, cold, drought, flooding, excess or lack of light, salinity, heavy metals, and mechanical injuries. In addition, they positively influence various quality parameters such as seed germination rate, seedling vigor, uniformity, and organoleptic traits like flavor, color, and nutritional content.

Medicinal and aromatic plants (MAPs) have gained attention for their biostimulant potential due to their rich phytochemical profiles. Extracts from *Hypericum perforatum* have significantly enhanced chlorophyll content, antioxidant capacity, and overall growth and yield in *Apium graveolens* and *Brassica oleracea* (Godlewska *et al*., 2020; Godlewska *et al*., 2021).

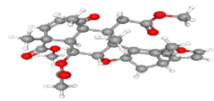
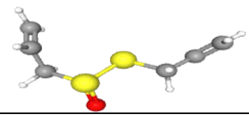
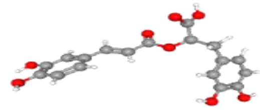
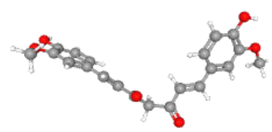
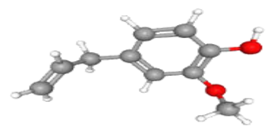
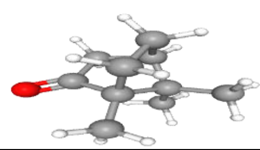
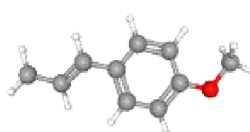
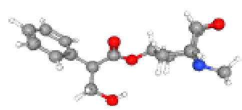
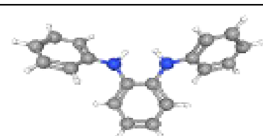
Likewise, seed priming with *Rosmarinus officinalis* demonstrated improvements in germination, early seedling growth, and antioxidant enzyme activity in *Zea mays* under salt stress conditions (Panuccio *et al*., 2018). Foliar applications of rosemary essential oil have also shown to increase shoot and root biomass and boost nutrient uptake in tomato plants (*Solanum lycopersicum*) (Souri and Bakhtiarizade, 2019).

Despite promising advancements, the intricate molecular and biochemical mechanisms by which these plant-derived extracts function remain to be thoroughly elucidated. Further research is needed to validate and characterize these effects for broader agricultural applications. The common Medicinal and Aromatic Plants with Biopesticidal, Antimicrobial, or Biostimulant Properties have given in Table 1.

Medicinal and Aromatic Plants Uses in Nanobiotechnology

The increasing demand for efficient, sustainable, and precise agricultural practices has fostered the growth of interdisciplinary fields such as nanobiotechnology, which focuses on engineering materials at the nanoscale (1–100 nm). The term "nano" originates from the Greek word for "dwarf," indicating extremely small dimensions (Bayda *et al*., 2019). Nanoparticles offer improved delivery systems for agrochemicals such as pesticides, fertilizers, and biostimulants, by enhancing their solubility, stability, and targeted release (Balusamy *et al*., 2023). These nanomaterials can stabilize hydrophobic substances and allow for slow, controlled nutrient delivery.

Table.1 Common Medicinal and Aromatic Plants with Biopesticidal, Antimicrobial, or Biostimulant Properties

S. No.	Plant Name (*Botanical Name*)	Active Compounds	Chemical Formula	Chemical Structure	Agricultural Application
1	Neem (*Azadirachta indica*)	Nimbin	• $C_{30}H_{36}O_9$		Biopesticide, Antifungal
2	Garlic (*Allium sativum*)	Allicin	$C_6H_{10}OS_2$		Antibacterial, Insect-repellent
3	Rosemary (*Rosmarinus officinalis*)	Rosmarinic acid	$C_{18}H_{16}O_8$		Growth stimulant, Stress tolerance, inhibit growth of weeds like *Amaranthus retroflexus*
4	Turmeric (*Curcuma longa*)	Curcumin	$C_{21}H_{20}O_6$		Antimicrobial, Soil health enhancer, Inhibit germination and growth of *Cortaderia selloana*
5	Tulsi (*Ocimum sanctum*)	Eugenol	$C_{10}H_{12}O_2$		Insecticidal, Seed treatment
6	Crown Daisy (*Chrysanthemum coronarium)*	Camphor	$C_{10}H_{16}O$		Inhibit growth of weed *Phalaris canariensis*, *Sinapis arvensis*
7	Coriander *(Coriandrum sativum)*	*trans*-Anethole	$C_{10}H_{12}O$		Inhibit growth of weed *Avena fatua*
8	Thorn apple *(Datura stramonium)*	Scopolamine	$C_{17}H_{21}NO_4$		Inhibit germination of weeds
9	Long pepper *(Piper longum)*	Sarmentine	$C_{17}H_{25}NO$		Inhibit growth of weeds such as *Abutilon theophrasti*, *Amaranthus retroflexus*,

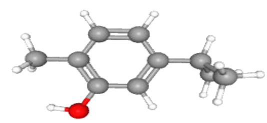
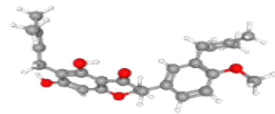
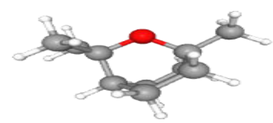
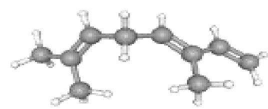
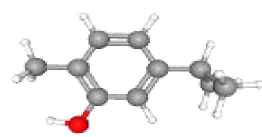
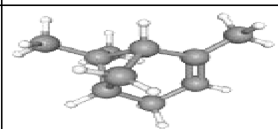
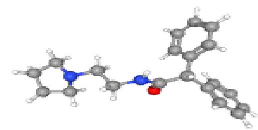
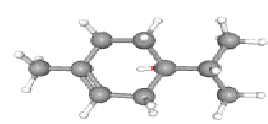
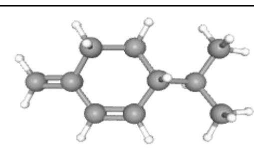
10	Thyme (*Thymus vulgaris)*	Carvacrol	• $C_{10}H_{14}O$		Inhibit growth and germination of *Capsicum annuum*, *Chenopodium album*,
11	Ginger (*Zingiber officinale*)	β-Bisabolene	• $C_{26}H_{30}O_5$		Inhibit growth and germination of *Cortaderia selloana*, *Lolium multiflorum*, *Portulaca oleracea*
12	Peppermint *(Mentha piperita)*	1,8-Cineole,	• $C_{10}H_{18}O$		Inhibit growth and germination of *Convolvulus arvensis*, *Echinochloa colona*,
14	Hemp / Marijuana (*Cannabis sativa*)	(E)-β-ocimene	• $C_{10}H_{16}$		Inhibit germination and growth of *Bromus secalinus*
15	emongrass (*Cymbopogon citratus*)	carvacrol	• $C_{10}H_{14}O$		Inhibit germination and growth of *Amaranthus palmeri, Amaranthus blitoides,*
16	Fennel (*Foeniculum vulgare*)	α-Pinene	• $C_{10}H_{16}$		Inhibit germination and growth of *Amaranthus retroflexus, Portulaca oleracea*
17	Basil (*Ocimum basilicum*)	iso-pinocamphone	• $C_{20}H_{24}N_2O$		Inhibit germination and growth of *Amaranthus retroflexus, Lactuca sativa, Lepidium sativum,*
18	Oregano (*Origanum vulgare*)	γ-terpinene	$C_{10}H_{16}$		Inhibit germination and growth of *Lactuca sativa*, *Lepidium sativum*, *Raphanus sativus*,
19	Parsley (*Petroselinum crispum*)	β-phellandrene	• $C_{10}H_{16}$		Inhibit germination and growth of *Lactuca sativa*

Table.2 Applications of Medicinal and Aromatic Plants in Nanoparticle Synthesis

S. No.	Plant Used	Type of Nanoparticle Synthesized	Role in Synthesis	Agricultural Relevance
1	*Azadirachta indica*	Silver nanoparticles	Reducing + Capping agent	Antibacterial nanoformulations
2	*Ocimum basilicum*	Gold nanoparticles	Reducing agent	Biosensors, seed coating
3	*Mentha piperita*	Zinc oxide nanoparticles	Stabilizing + Reducing agent	Nano-fertilizer
4	*Zingiber officinale*	Silver nanoparticles	Antioxidant-mediated synthesis	Antimicrobial foliar spray
5	*Lawsonia inermis*	Iron oxide nanoparticles	Bio-template + Capping	Soil amendment, root health booster

Table.3 Comparative Benefits of MAP-Based Products vs. Conventional Agrochemicals

Sl No	Parameter	MAP-Based Products	Conventional Agrochemicals
1	Environmental Impact	Low to minimal	High (often polluting)
2	Biodegradability	High	Often non-biodegradable
3	Resistance Development in Pests	Rare	Frequent
4	Safety to Humans and Livestock	Generally safe	Often toxic
5	Mode of Action	Multifunctional (biostimulant + antimicrobial)	Single-target
6	Cost in Long Term	Cost-effective due to reuse of by-products	High due to repeated applications

Common nanoparticles used in agriculture include polymeric nanoparticles, silver nanoparticles, nano alumino-silicates, titanium dioxide, and carbon-based nanostructures (Bratovcic *et al*., 2021). Despite their numerous benefits, concerns about the environmental and health impacts of nanoparticles persist. Due to their high reactivity and ability to penetrate biological systems, nanoparticles can accumulate in the food chain, posing risks to human health and ecological balance (Zulfiqar *et al*., 2019). Moreover, their transformations in environmental matrices may generate harmful byproducts, necessitating careful assessment.

To reduce these risks, green synthesis methods involving biological sources such as plant extracts are gaining attention (Castillo-Henriquez *et al*., 2020). These eco-friendly approaches utilize the antioxidant-rich profiles of medicinal and aromatic plants (MAPs)—including flavonoids, phenolics, and alkaloids—as natural reducing and stabilizing agents during nanoparticle synthesis. The biosynthesis process generally follows three steps: activation (reduction of metal ions), growth (agglomeration into stable particles), and termination (final stabilization and size control) (Makarov *et al*., 2014).

MAP extracts not only facilitate the conversion of metal ions into nanoparticles but also act as capping agents to prevent particle aggregation, thereby improving stability. This reduces dependency on hazardous chemical agents, promoting environmentally friendly nanotechnology. However, due to the complex composition of plant extracts, achieving uniform particle size and morphology can be challenging (Khan *et al*., 2023).

While promising results have emerged, further research is needed to better understand the biosynthesis mechanisms and to adapt nanobiotechnological advancements for practical agricultural applications. The applications of MAPs in nanoparticle synthesis is summarised below in Table 2.

The benefits of MAP based Products over Conventional Agrochemicals have been given in the Table 3.

In conclusion, extensive research on medicinal and aromatic plant (MAP) extracts highlights their significant potential as eco-friendly and sustainable alternatives in modern agriculture. These plant-derived compounds offer multifaceted benefits—ranging from pest, disease, and weed management to improved plant resilience against abiotic and biotic stresses. Moreover, MAPs act as effective bio-stimulants by enhancing plant growth, nutrient uptake, stress tolerance, and overall crop quality. Their role in sustainable nano-biotechnology further broadens their applicability, providing an environmentally safer approach to nanoparticle synthesis. As agriculture faces increasing pressure to boost productivity while reducing environmental impact, the integration of MAP-based solutions offers a promising avenue for future innovations in green farming practices. Continued research and field-level validation are essential to fully harness their capabilities in large-scale agricultural systems.

Future Outlook

Looking ahead, the integration of medicinal and aromatic plant (MAP) extracts into mainstream agricultural practices presents a transformative opportunity for sustainable farming.

However, to realize their full potential, further research is essential to standardize extraction methods, optimize dosages, and understand their interactions with crops, soils, and the environment. Advancements in formulation technology, especially in combination with nanobiotechnology, can enhance the efficacy and stability of these bioactive compounds. Moreover, interdisciplinary collaborations among botanists, agronomists, chemists, and environmental scientists are crucial to developing MAP-based products that are not only effective but also economically viable and safe for long-term use.

Scaling up from laboratory to field applications, supported by regulatory frameworks and farmer awareness programs, will be pivotal in establishing MAPs as core components of future sustainable agricultural systems.

Author Contributions

Dr Snigdharani Dash: Conceived the original idea, gather the resources, analysed the data, writing- review and editing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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