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MEDICINAL PLANT-DERIVED ANTIPATHOGENIC COMPOUNDS IN PHYTOPATHOGEN MANAGEMENT: MECHANISMS, APPLICATIONS AND FUTURE PERSPECTIVES

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ABSTRACT
The increasing incidence of fungal, bacterial and viral phytopathogens coupled with the growing resistance to conventional synthetic chemicals presents a serious risk to both environmental sustainability and global crop productivity. antipathogenic compounds shown promise as environmentally and friendly substitutes. However, their application in crop protection remains constrained by limiting their modes of action, lack of standardization and inconsistent field performance. The brief summary of plant-derived antipathogenic compounds and their functions in phytopathogen management is provide in this article. Numerous classes of biologically active metabolites like alkaloids, phenolics, flavonoids, terpenes, saponins and sulfur-containing compounds, were discussed in relation to their wide range of mechanism, such as membrane disruption, metabolic interference, suppression of pathogen development, and induction of host resistance. Recent advances in formulation strategies, particularly nano-based delivery systems and synergistic integration with biological control agents, are highlighted for improving stability, bioavailability, and efficacy. Key limitations, including variability in phytochemical composition and inadequate field validation, are critically examined. All things considered, this study offers a strategy framework to close the gap between field application and laboratory research, facilitating the creation of long-term, plant-based remedies for efficient phytopathogen control.

KEYWORDS: Bioactive compounds; Plant defence mechanism; Nano-formulation; Biocontrol agents; Crop protection.

1. INTRODUCTION
Medicinal plants play an essential role in day-to-day human life, since medicinal plants have been used by half of the world's population. to treat various health issues since ancient times, and this practice is receiving considerable attention in the field of global health (Mongalo *et al*., 2016). According to Ministry of Environment, Forests, and Climate Change's Botanical Survey of India (BSI), moreover 8000 species of medicinal plants are present in India alone, and 2,500 of those species are used to make various traditional medicines (Goraya & Ved, 2017; Paroda *et al*., 2014). Medicinal plants have a variety of bioactive compounds, known as secondary metabolites, such as alkaloids, phenolic compounds, flavonoids, terpenes, saponins, and sulfur-containing secondary metabolites are examples of secondary metabolites, which protect the body from both biotic and abiotic stress, making them vital for plant survival even if they are not necessary for plant growth. These bioactive compounds act as antipathogenic compounds by targeting key metabolic and signalling pathways in humans, pathogens, and microbes (Mickymaray, 2019). Secondary metabolites are estimated at approximately 2.14M known compounds across all biological sources, classified mainly into terpenoids and steroids (over 35,000; 25,000 in plants specially), alkaloids (over 12,000), and other groups including fatty acid-derived substances, phenolics (approx. 8,000), flavonoids, and tannins, many of which remain under continued characterization (Thirumurugan *et al*., 2018; Upadhyay *et al*., 2015). Commercial formulations derived from medicinal plants offer eco-friendly and efficient substitutes for controlling plant diseases, yet their field-level adoption remains limited. This is largely due to inadequate awareness among farmers regarding their efficacy, application methods, and long-term benefits. Improved extension services and scientific outreach are vital to increase their uptake and application in sustainable agriculture.
In past years, medicinally derived formulations and extracts have been attracting scientific and commercial consideration as substitutes for artificial fungicides in the control of plant diseases. These plants are widely available, and their extracts can be prepared using simple, low-cost methods without specialised equipment, making the resulting natural fungicides accessible and economical.
Notably, complete inhibition of *Monilia fructigena* conidiospores can be achieved at lower concentrations than those required for most synthetic fungicides (Hernández-Soto *et al*., 2025). Garlic water extract showed the highest potential

for protecting stored seed potatoes, demonstrating wide-spectrum antimicrobial activity in *in vitro* and *in situ* against phytopathogens. The inexpensive cost of production is an additional benefit of employing these extracts (Steglińska *et al*., 2022). The ability of *Alpinia zerumbet* to combat plant viruses was evaluated as a potential antiviral compound using Nicotiana benthamiana plants infected with GFP-tagged *Tomato Mosaic Virus* (ToMV) (Hatanaka *et al*., 2021).

LITERATURE SEARCH METHODOLOGY:

The literature search and article selection were conducted using the Scopus database. The search strategy was developed by combining the keywords "Medicinal plants" AND "Bioactive compounds" OR "Plant protection." Scopus was selected as the primary database because of its broad multidisciplinary coverage and extensive indexing of peer-reviewed literature in agricultural, biological, biochemical, and related scientific fields.

The search was limited to publications published between 2018 and 2026. The inclusion criteria comprised articles, reviews, and book chapters published in English; records from journals, books, and book series; and publications in the final publication stage. Only open-access documents were included. Relevant subject areas included Medicine, Biochemistry, Genetics and Molecular Biology, Agricultural and Biological Sciences, and Multidisciplinary studies. Publications classified under unrelated subject areas, including Pharmacology, Toxicology and Pharmaceutics, Chemical Engineering, Nursing, Social Sciences, Economics, Econometrics and Finance, Energy, Neuroscience, and Computer Science, were excluded. Short surveys, non-English publications, and restricted-access documents were also excluded.

The retrieved records were subsequently screened based on their titles and abstracts to identify studies containing the predefined keywords in the title, abstract, or keyword section. The potentially relevant articles were further assessed through full-text screening, and only studies directly relevant to medicinal plants, their bioactive compounds, and their role in plant protection were retained for the final analysis. The complete inclusion, exclusion, and screening criteria are presented in Table 1, while the overall article selection process is summarized in Figure 1.

Table 1: The inclusion and exclusion criteria for literature search strategy

Criteria	**Inclusion**	**Exclusion**
Time period	2018-2026	<2018
Subject area	Medicine, Biochemistry, Genetics and Molecular Biology, Agricultural and Biological Sciences, Multidisciplinary.	Pharmacology, Toxicology, and Pharmaceutics, Chemical Engineering, Nursing, Social Sciences, Economics, Econometrics, and Finance, Energy, Neuroscience, and Computer science.
Document type	Article, review, book chapter	Short survey
Languages	English	Non-English
Source type	Journal, Book, Book series	-
Publication stage	Final	Press
Open access	All Open access	Restricted access
Screening		
Title and abstract	Existence of predefined keywords in the title, abstract, or keywords part of the paper	-
Full text	Included relevant papers that discuss the predefined keywords	-

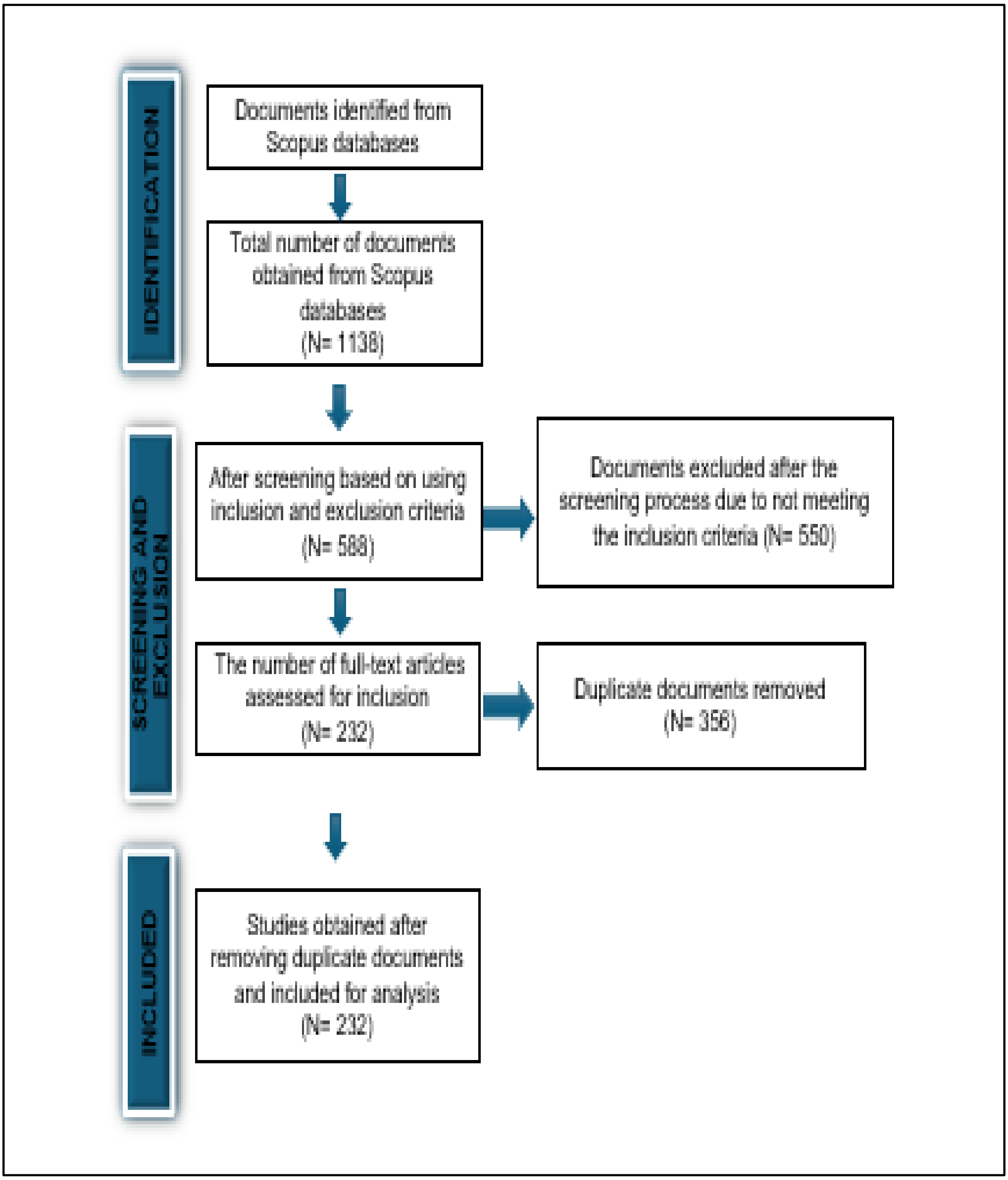

Figure 1: Flowchart of the study selection process for literature retrieved from the Scopus database.

India's medicinal plant distribution:

The therapeutic plants can be found in a range of environments and landscape features, according to the distribution analysis. In India, Sikkim encompasses diverse ecological zones, from tropical to alpine, supporting rich floral and faunal diversity. Together with the Darjeeling hills, Sikkim harbours over 700 medicinal plant species. These plants form a valuable resource for both traditional medicine and biodiversity conservation (Badola & Aitken, 2003).

More than 70% of India's medicinal plants are found in the tropical forests of the Eastern and Western Ghats, the Chota Nagpur Plateau, the Aravalis, the Vindhyas, and the Himalayas. Nestled in the northwest folds of the Himalayas, which were recently named a global biodiversity hotspot, is the Kashmir Himalayan region. (Mittermeier *et al.*, 1999). The distribution range of medicinal plants is illustrated in detail (Figure. 2)

Figure 2. Geographical distribution of species of medicinal plants in India's various regions

Pathogens as an emerging threat to agricultural productivity

Fungal diseases in plants produce mycotoxins that contaminate the food supply and account for about 20% of annual crop losses; nevertheless, antifungal treatments increase resistance and carry toxicity hazards (Khan *et al*., 2023). Over 200 bacterial pathogens cause plant diseases that reduce crop quality and output, accounting for about 10% of global production losses (over USD 1 billion annually) (Rai & Rai, 2025). Through leaf damage, decreased fruit quality, and in extreme situations, complete crop loss, more than 2,100 plant viruses result in substantial financial losses. Climate variability exacerbates viral infections, which are spread by insects, mites, nematodes, fungus, and mechanical damage. To guarantee food security, integrated management techniques are crucial (Singh *et al*., 2024). One of the methods is to use of antipathogenic compounds from medicinal herbs to control the emerging threat, as they possess antifungal, antibacterial, and antiviral activities. Fungal, bacterial, and viral pathogens represent critical threats to agricultural productivity is illustrated in (Fig.3)

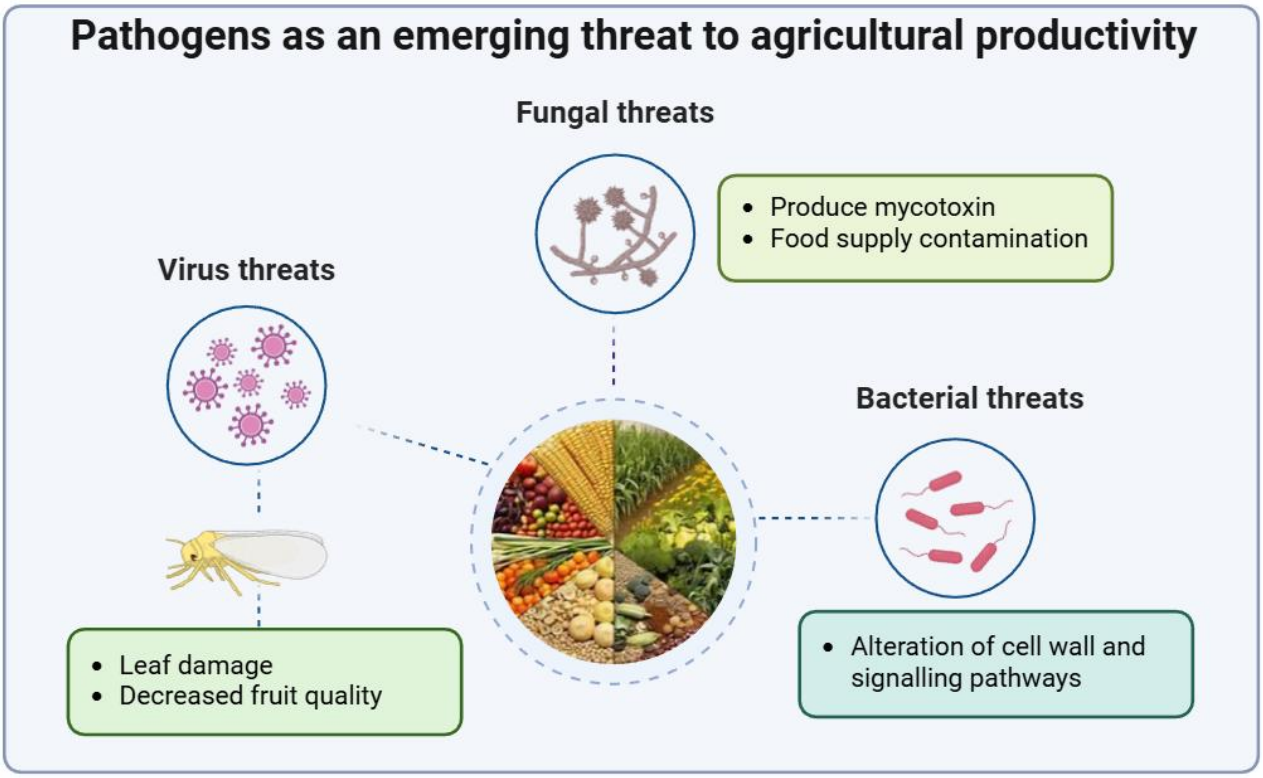

Figure 3. Overview of emerging pathogenic threats to agricultural productivity, illustrating the effects of fungal, bacterial, and viral pathogens on crops

Major Secondary metabolites from medicinal plants

When exposed to wide range of microorganisms in the wild, plants create several defence mechanisms to fend them off. These antagonists can be abiotic (such as cold, heat, salt, and water stress, as well as mineral and nutritional deficiencies) or biotic (such as fungi, bacteria, and viruses). Numerous defensive mechanisms have evolved in plants against pathogenic strike, including the production of toxins, enzyme secretion, and penetration barriers (Yang *et al*., 2018). Secondary metabolites obtained from plants play a crucial role in defence mechanisms (Jibril *et al*., 2016). Plants develop defensive chemicals in response to various stressors, which have coevolved with millions of secondary metabolites (Khare *et al*., 2020). There are about two million SMs that plants make, although this is a small quantity in comparison to the 3,91,000 plant species that are now known to exist. Depending on their properties, secondary metabolites can be categorised in a number of ways. One common approach is based on their chemical composition, such as whether they contain nitrogen or not. They may also be grouped according to their chemical structure, for example, the presence of ring systems or sugar moieties. Another basis for classification is the biosynthetic pathway that leads to the production of tannins. In addition, their solubility properties are sometimes considered. In general, there are three main kinds of secondary metabolites: alkaloids, Terpenes, and Phenolic compounds (Alamgir, 2017; Kabera *et al*., 2014). Numerous kinds of chemicals, including alkaloids, phenolics, polyphenols, flavonoids, quinones, tannins, coumarins, terpenes, lectins, polypeptides, and saponins, are found throughout the nature (Alamgir, 2017; Katz & Baltz, 2016; O'Connor, 2015). In addition, they can act synergistically with conventional antibiotics, thereby improving their efficacy and lowering the chance of developing antibiotic resistance (Bribi, 2018). The major compounds found in plants are phytochemicals, particularly secondary metabolites, which play a crucial role as antipathogenic compounds and controls the pathogen activities is given in (Figure 4).

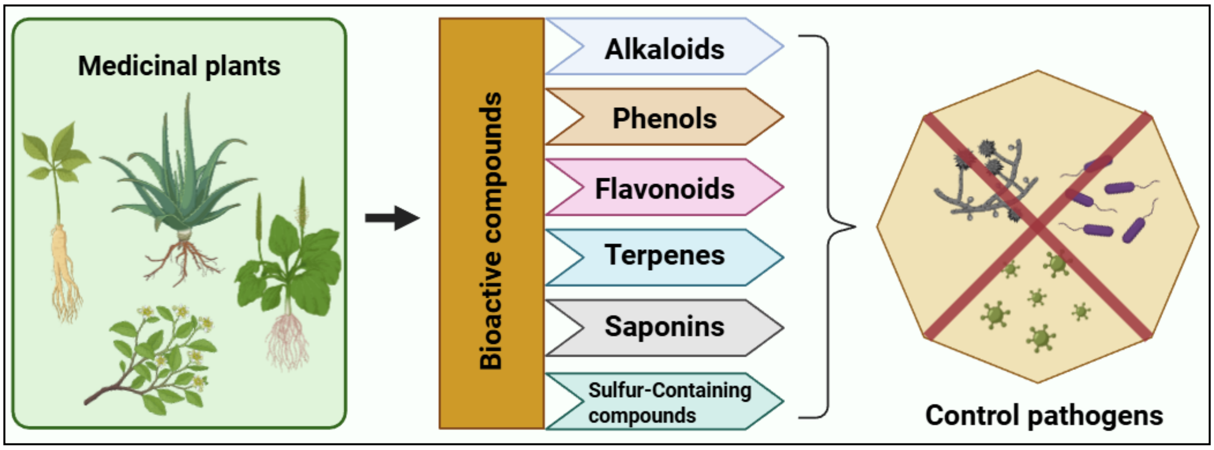

Figure 4. Conceptual illustration showing medicinal plants as sources of diverse bioactive compounds, including alkaloids, phenols, flavonoids, terpenes, saponins, and sulfur-containing compounds, which contribute to effective management of plant pathogens.

Alkaloids

About 20% of active metabolites are derived from medicinal plants were alkaloids (Dey *et al*., 2020). It possesses an N-heterocyclic nitrogen structure, which comes from amino acids like tyrosine and tryptophan (Othman *et al*., 2019). Alkaloids were primarily found in dicots and monocots; they are absent from lower plants such as mosses and ferns (Sulaiman *et al*., 2022). Alkaloids may reduce the likelihood that fungal populations may develop resistance due to their diverse chemical structures and modes of action (such as DNA damage, interruption of membrane integrity, inhibition of enzymes important for fungal metabolism, and crushing of cell wall construction) (Dozio *et al*., 2025). Similarly, alkaloids build up during pathogen infection and give the plant resistance. For example, three major alkaloids, pegamine, harmol, and harmine, characterised from the medicinal plant of *Peganum harmala*, display the lowest bactericidal and inhibitory doses against *Ralstonia solanacearum* Phylotype II, which leads to damage of bacterial cells, disruption of cytoplasm, clumping of genetic material and thickening of the cell wall compared to control cells (Shaheen & Issa, 2020).

Phenolic compounds

These secondary metabolites, known as phenolic compounds, feature phenolic and hydroxyl functional groups on an aromatic ring. They play protective roles in plants, aiding growth, reproduction, seed germination, and defence against diseases and predators (Gautam *et al*., 2020). Plant protection happens in two stages: The manufacture of certain polyphenolics and other secondary metabolites that restrict the pathogen at the infection site, as well as the accumulation of phenols at the infection site that prevents the pathogen from developing (Bhonwong *et al*., 2009). Through the synthesis of a number of proteins linked to disease and the mediation of hypersensitive reaction-mediated cell death, polyphenolic substances offer resistance to certain microorganisms. By altering membrane permeability, cell wall integrity, enzyme activity, production of free radicals, inhibition of protein biosynthesis, DNA damage, and decreasing the expression of pathogenic genes (Ansari *et al*., 2014; Fernandes *et al*., 2019; Negritto *et al*., 2017; Upadhyay *et al*., 2015). The mixed extracts of *Eucalyptus camaldulensis, Chromolaena odorata*, *Bidens Pilosa*, and *Azadirachta indica* were shown to contain a high concentration of phenolic chemicals. These extracts contain a number of physiologically active substances, such as gallic acid, chlorogenic acid, p-coumaric acid, ferulic acid, and quercetin. The mixture of plant extracts demonstrated significant antifungal efficacy in lab testing, preventing *Fusarium oxysporum* growth up to 83.13%. After 28 days of inoculation, the extract dramatically lowered the disease index in tomato plants by roughly 26.7-28.0% (Nguyen *et al*., 2024).

Flavonoids

One important class of polyphenolic compounds is flavonoids, with over 9,000 identified variants displaying a range of biological functions, including antioxidant, antifungal, and antibacterial properties (Ullah *et al*., 2020). They serve as water-soluble pigments and are categorised into 12 subgroups, influencing plant colouration and protecting against environmental stresses (Liu *et al*., 2021). By disrupting the cell wall, damaging membranes, causing cell death, inhibiting enzyme activity, chelating metal ions, binding extracellular proteins, and inhibiting the efflux pump, flavonoids protect against fungal infections (Al & Mickymaray, 2020). In *Populus alba* var. pyramidal, transcription factors were overexpressed and the synthesis of phenols, proanthocyanidins (PAs), anthocyanins, quercetin, kaempferol, and the antioxidant enzymes superoxide dismutase and peroxidase were increased by PalbHLH1 and PalMYB90. This series of actions provides defence against infections with *Dothiorella gregaria* and *Botrytis cinerea* (Bai *et al*., 2020).

Terpenes

Terpenes are the biggest and most utilised class of secondary metabolites. Terpenes' varied properties have led to their employment in a wide range of applications since they carry out specific chemical tasks that shield plants from biotic and abiotic stressors (Roba, 2020). Terpenes play a crucial for plant protection against various stresses and are prevalent in nature, comprising over 22,000 compounds (Tiku, 2018). They come from 5-carbon isopentenoid units and are divided into groups like monoterpenes and sesquiterpenes according to the number of isoprene units (Ahmed *et al*., 2017; Mishra *et al*., 2024). Terpene synthesis is driven by two precursor molecules: the isopentenyl diphosphate (IPP) unit and its isomer, dimethylallyl diphosphate (DMAPP) (Abdallah & Quax, 2017). Upon the GC-MS results of *Thymus vulgaris*, the monoterpenoid compound identified as thymol shows inhibitory activity against *Fusarium oxysporum* f. sp. *Lactucae* (Omar *et al*., 2021).

Saponins

Saponins, a class of terpenoid secondary metabolites, possess diverse biological activities that aid in managing various biotic and abiotic stressors (Iovinella *et al*., 2023). Saponins are classified into steroidal and terpenoid types, with a correlation observed between their composition and specific pests. Pathways that generate dimethylallyl diphosphate (DMAPP) and isopentenyl pyrophosphate (IPP) are involved in their production (Noushahi *et al*., 2022). The defence role of saponins works by interfering with the cell membranes' normal function and integrity. They cause structural damage and increased permeability through their interactions with membrane components. When fresh membrane synthesis occurs during active cell growth, this effect can intensify (Yendo *et al*., 2025). *Chenopodium quinoa's* triterpenoid saponins shielded tomato plants from Fusarium wilt (Zhou *et al*., 2023).

Sulfur-containing secondary metabolites

By acting as either phytoalexins or phytoanticipants, sulfur-containing secondary metabolites support plant defence against harmful microorganisms. Glucosinolates, thiosulfinates like allicin made from cysteine sulfoxides, and antimicrobial peptides such defensins and thionins (Tiku, 2018) are important examples. Allicin, ajoene, dialkenyl and dialkyl sulphides, S-allyl cysteine, S-allyl-mercaptocysteine, and isothiocyanates are a few sulfur-containing substances that have demonstrated potent antibacterial action against a wide range of Gram-positive and Gram-negative bacteria (Ashraf *et al*., 2023; Boghrati & Iranshahi, 2019). Many sulfur-containing secondary metabolites are volatile, pungent, or odorous. They are classified into two groups based on their biosynthetic pathways. In the first group, glucosinolates are produced through myrosinase-catalysed hydrolysis, common in the Cruciferae family, including cabbage, broccoli, and nasturtium. In the second group, allin is formed via allinase-mediated hydrolysis, typical of the genus Allium, such as garlic, leeks, and onions. These two routes are important in reducing herbivore damage and avoiding pathogen attack (Sayadi *et al*., 2020). Isothiocyanates are sulfur-containing bioactive compounds obtained from *Brassica* sp has the inhibitory activity on mycelial and conidial germination of *Fusarium graminearum*, affecting most of the cereal crops (Ashiq *et al*., 2022).

Multitarget mechanisms of plant-derived antipathogenic compounds against phytopathogens:

A variety of compound-specific mechanisms, such as membrane inhibition, oxidative stress induction, interference with nucleic acid synthesis, disruption of quorum sensing, and activation of host defence responses, are used by plant-derived antipathogenic compounds to combat phytopathogens are illustrated in (Fig.5)

Membrane disruption:

Carvacrol and thymol, phenolic compounds derived from *Origanum vulgare*, strongly inhibited *Botrytis cinerea* and completely suppressed spore germination at 300 μg/mL. Scanning electron microscopy revealed severe collapse and structural damage of fungal mycelia following treatment. Increased extracellular conductivity further confirmed disruption of fungal membrane integrity and enhanced leakage of intracellular contents. These morphological and conductivity-based findings provide direct experimental evidence of membrane damage. In tomato fruits, both compounds also reduced gray-mold development. Thus, disruption of fungal membrane integrity is an experimentally supported mechanism underlying the antifungal activity of carvacrol and thymol against *B. cinerea* (Hou *et al*., 2020).

Oxidative stress and Mitochondrial Dysfunction:

Honokiol, a phenolic compound derived from the medicinal plant *Magnolia officinalis*, strongly inhibited spore germination and mycelial growth of *Aspergillus flav*us, with complete inhibition of spore germination at 100 μg/mL, and reduced conidia production in corn flour. Fluorescence staining and biochemical analyses revealed increased intracellular reactive oxygen species (ROS), mitochondrial dysfunction, and enhanced plasma-membrane permeability following treatment. Transcriptomic analysis identified 1,578 differentially expressed genes associated with oxidative stress, energy metabolism, cell-wall integrity, and membrane function, with selected genes further validated by qRT-PCR. Collectively, these physiological, biochemical, microscopic, and transcriptomic findings demonstrate that ROS accumulation and oxidative-stress-associated mitochondrial dysfunction contribute to the antifungal activity of honokiol against *A. flavus* (Zhang *et al*., 2023).

Inhibition of Biofilm formation:

7-Methoxycoumarin, a plant-derived coumarin, exhibited antibacterial activity against *Ralstonia solanacearum*, with a minimum inhibitory concentration (MIC) of 75 mg/L and a minimum bactericidal concentration (MBC) of 175 mg/L. Electron microscopy revealed pronounced destruction of the bacterial cell membrane, while sub-inhibitory concentrations markedly reduced biofilm formation. Molecular analysis further showed significant downregulation of the virulence-associated genes epsE, hrpG, and popA. In pot experiments, 7-methoxycoumarin achieved 83.61% relative control efficiency against bacterial wilt of tobacco at 6 days after inoculation. Collectively, these findings demonstrate that 7-methoxycoumarin suppresses *R. solanacearum* through membrane disruption, inhibition of biofilm formation, and downregulation of virulence-associated genes, with its activity further confirmed under in planta conditions (Han *et al*., 2021).

Interference with Viral Nucleic Acid Synthesis:
Seco-pregnane C_{21} steroidal glycosides isolated from the medicinal plant *Cynanchum paniculatum* exhibited strong antiviral activity against *tobacco mosaic virus* (TMV) in *Nicotiana tabacum*. Among the isolated compounds, compounds 1, 2, 5, 9, 10, 15, and 16 significantly inhibited TMV infection and showed greater activity than the positive control, ningnanmycin. RT-PCR analysis revealed reduced replication of the TMV coat-protein (TMV-CP) gene, while Western blotting confirmed a corresponding decrease in TMV-CP protein accumulation. The compounds also suppressed the expression of the host genes NtHsp70-1 and NtHsp70-261, which are associated with TMV infection. Collectively, these antiviral and molecular analyses provide experimental evidence that these steroidal glycosides interfere with TMV nucleic acid replication and subsequent viral protein accumulation (Yan *et al*., 2022).

Viral particle disruption and coat protein targeting:
Vanillic acid, isolated from the medicinal plant *Hyoscyamus niger*, exhibited strong antiviral activity against *tobacco mosaic virus* (TMV) in *Nicotiana tabacum*. At 125–500 µg/mL, it showed substantial TMV inactivation and protective activity, with inhibitory rates ranging from 47.30–79.71% and 43.28–63.87%, respectively. Microscopic observations revealed that vanillic acid directly disrupted TMV particles into smaller fragments, while molecular analysis showed reduced transcription of the TMV coat-protein (TMV-CP) gene. The TMV coat protein was identified as a principal antiviral target. Collectively, these findings provide experimental evidence that direct disruption of viral particles and targeting of the viral coat protein contribute to the antiviral activity of vanillic acid against TMV (Hu *et al*., 2022).

Cell membrane and Cell wall integrity:
Euphorbia factor L_3 (EFL_3), isolated from the medicinal plant *Euphorbia lathyris*, showed strong inhibitory activity against *Phytophthora capsica*. Propidium iodide and calcofluor-white staining demonstrated disruption of cell-membrane and cell-wall integrity, while increased conductivity, MDA, and glycerol levels indicated membrane damage and cellular leakage. EFL_3 also significantly reduced phospholipid and cellulose contents. Furthermore, protective and curative activity was confirmed in tomato and pepper assays. Collectively, these findings demonstrate that cell-wall and cell-membrane disruption, accompanied by reduced phospholipid and cellulose biosynthesis, contributes to the anti-*P. capsici* activity of EFL_3 (Wang *et al*., 2023).

Quorum quenching:
Rhapontigenin, a stilbenoid from medicinal *Rheum* spp., attenuated the virulence of *Pectobacterium carotovorum* subsp. *carotovorum* by disrupting AHL-mediated quorum sensing (Li *et al*., 2022). At sub-MIC levels, it markedly reduced AHL and violacein production, biofilm formation, motility, EPS production, and QS-regulated exoenzyme activities without affecting bacterial growth. LC–MS and microscopic analyses further confirmed reduced AHL signaling and impaired biofilm development. Moreover, rhapontigenin reduced soft-rot symptoms in Chinese cabbage and lettuce. Collectively, these findings provide experimental evidence that rhapontigenin suppresses AHL-mediated quorum sensing, thereby reducing biofilm formation and bacterial virulence (Li *et al*., 2022).

Disruption of Metabolic pathways:
Cinnamaldehyde, a major bioactive constituent of medicinal Cinnamomum species, disrupted metabolic homeostasis in *Phytophthora capsica*. Quantitative iTRAQ proteomic analysis identified 1,502 differentially expressed proteins, with significant alterations in pathways related to fatty-acid, polysaccharide, leucine, and glyoxylate/dicarboxylate metabolism. These changes were further confirmed by parallel-reaction monitoring and qRT-PCR analyses. Collectively, the results provide experimental evidence that cinnamaldehyde alters essential metabolic pathways and disrupts the biochemical homeostasis of P. capsici, contributing to its inhibitory activity (Wang *et al*., 2021).

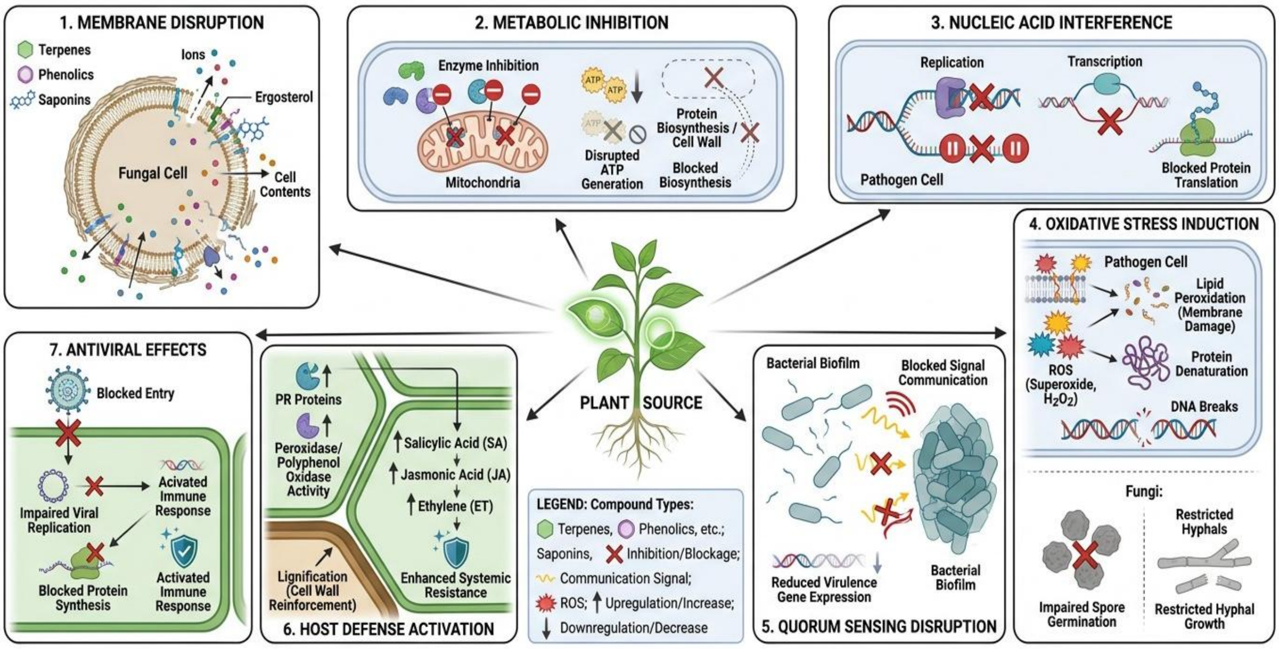

Figure 4: Plant-derived Antipathogenic compounds multitarget mechanisms against phytopathogens

Applications in phytopathogen management:

Medicinal plants used to treat fungal infections:

In recent years, increasing attention has been directed toward developing plant-based antimicrobial agents to control the harmful effects caused by pathogenic microorganisms (Bashir, 2012). Fungi are among the most significant plant infections and one of the main reasons why fruits and vegetables deteriorate, causing significant financial losses. Additionally, because fungi produce toxic mycotoxins, they pose a threat to human and animal health (Gakuubi *et al*., 2017; Khan *et al*., 2020). Postharvest losses occur when harvested fruits, vegetables, and seeds are damaged during handling, storage, or marketing, mainly due to pathogen infection favoured by moist and humid conditions. These infections typically begin either before harvest or during the postharvest stage (Porat *et al*., 2018). Medicinal plants have become the core of modern-day medicine, widely used as an alternative to synthetic fungicides. Several reports demonstrate that medicinal extracts probably reduce the mycelium formation and inhibit the germination of spores against the plant, causing fungi like *Fusarium oxysporum* by hindering the membrane integrity and metabolic pathways (Cherkupally *et al*., 2017; Hasan *et al*., 2020). Medicinal plants are available day by day, and their availability is easier for all smallholder farmers because of low-cost investment rather than chemical usage (Mulugeta *et al*., 2024; Nwafor *et al*., 2021). The aqueous extracts of *Acacia saligna* containing benzoic acid, caffeine, o-coumaric acid, naringenin, quercetin, and kaempferol strongly inhibited the mycelial growth of *Fusarium culmorum*, *Penicillium chrysogenum*, and *Rhizoctonia solani*, especially at high concentrations (Al-Huqail *et al*., 2019). *Fusarium oxysporum* f.sp. *Cyclaminis* was most suppressed by the aqueous extract of *Thymus vulgaris*. The primary components, including rosmarinic acid and caffeic acid, also showed more potent antifungal action (Ahmad & Matsubara, 2020). The antifungal activity of antipathogenic compounds from various medicinal plants is detailed in Table 2.

Table 2. Antipathogenic compounds extracted from medicinal plants and their fungal targets exhibit antifungal action.

S. No	Medicinal plant extracts	Biologically active compounds from medicinal plants	Target fungal Plant pathogens	Mechanism	Reference
1	Garlic (*Allium sativum*)	Diallyl trisulfide	Wood-decay/plant-associated fungi (*Trametes hirsuta, Laetiporus sulphureus*)	Disrupts and destabilizes fungal cell membrane integrity, impairing growth	(Gong *et al*., 2021)
2	Turmeric (*Curcuma longa*)	curcumin	*Candida* and *Aspergillus fumigatus*	Induces ROS production and apoptosis while inhibiting hyphal development	(Ahmed *et al*., n.d.)

				through the TUP1 pathway.	
3	*Acokanthera schimperi*	Alkaloids and sulfur compounds	*Peronospora destructor, Rhizoctonia solani,Fusarium oxysporum, Erysiphe, Sclerotinia sclerotiorum, Aspergillus niger*	Interfere with the growth of the fungal cell process	(Shehzadi *et al*., 2025)
4	*Syzygium cumini*	Phenolics, Terpenoids, Tannins and Saponins.	*Fusarium oxysporum, Aspergillus niger, Aspergillus flavus, Alternaria alternata*	Lipophilic phenolics damage fungal membranes, bind essential proteins/adhesins, and inhibit key fungal enzymes.	(Khadka *et al*., 2025)
5	*Albizia lebbeck*	Flavonoids, Phenolics	*Fusarium oxysporum* and other tomato pathogens	Phenolic- and flavonoid-rich bark extract inhibits pathogen growth and enhances antioxidant defense.	(Arasu *et al*., 2022)
6	*Acorus calamus*	asarone-Z	*Pestalotia psidii, Colletotrichum gloeosporioides, Alternaria alternata*	Essential oil suppresses fungal mycelial growth, with complete inhibition at higher concentrations.	(Devi *et al*., 2025)
7	*Zataria multiflora*	Thymol, carvacrol	*Fusarium oxysporum* f. sp. *vasinfectum*	Ethanolic extract reduces fungal mycelial growth as its concentration increases.	(Abrahim *et al*., 2025)
8	*Capparis spinosa*	alkaloids, flavonoids, polyphenols, steroids, saponins, tannins, glycosides, triterpenes, and phlobatannins	*Rhizoctonia solani, Macrophomina phaseolina, Fusarium graminearum, Alternaria alternata*	Suppresses fungal growth by disrupting cellular metabolism and membrane function through phytochemicals.	(Sharma *et al*., 2010)

Medicinal plants used to treat bacterial infections:

Secondary metabolites that therapeutic plants produce can combat pathogen infections. Phytopathogenic bacteria cause an annual economic loss of over $1 billion (Islam *et al*., 2024; Kannan & Bastas, 2015; Vicente *et al*., 2022). More than 200 species and more than 25 genera of bacteria are harmful to various plant species and result in large crop losses (Buttimer *et al*., 2017). The anti-bacterial activity that is extracted from the different medicinal plants could have the advantages of producing secondary metabolites to cure some bacterial infections in plants (Shresta *et al*., 2021). Linalool, a key component of thyme oil, breaks the cell membrane and inhibits the metabolic and oxidative respiratory mechanisms of bacterial pathogens. Hoxycoumarin inhibited bacterial growth of *Ralstonia solanacearum*, and the compounds effectively inhibited the virulence-associated genes epsE, hrpG, and popA, resulting in improved tobacco control of bacterial wilt (Pham *et al*., 2021). The detailed antibacterial activity of antipathogenic compounds is described in Table 3.

Table 3. Antipathogenic compounds extracted from medicinal plants and their bacterial targets exhibit antibacterial action

S. No	Medicinal plant extracts	Principal bioactive compounds	Bacterial plant pathogens	Mechanism	Reference
1	Garlic	Allicin, Phenolic acids (gallic acid, caffeic acid)	*Pantoea ananatis*	Phenolic compounds exert direct antibacterial effects while foliar application enhances plant defense enzymes, including peroxidase, polyphenol oxidase, and β-1,3-glucanase.	(Mikhail *et al*., 2025)
2	*Lantana camara*	Phenolics, Flavonoids	*P. ananatis*	Phenolic acids directly inhibit bacterial growth and enhance polyphenol oxidase activity in plants.	(Mikhail *et al*., 2025)
3	Garlic	Allicin	*Ralstonia solanacearum*	Methanol extracts most effective solvent for direct antibacterial suppression of pathogen growth	(Mutimawurugo *et al*., 2020)
4	Anise (*Pimpinella anisum,* essential oil)	Anethole	*R. solanacearum*	Inhibits bacterial growth in vitro and enhances plant defense enzymes (PO and PPO) in vivo, thereby reducing disease incidence and severity.	(Abd-Elrahim *et al*., 2022)
5	*Albizia lebbeck* bark extract	Flavonoids and Phenolics	*Xanthomonas campestris pv. vesicatoria / speck pathogens on tomato*	Phenolic- and flavonoid-rich extract suppresses pathogen growth and reduces disease severity under greenhouse conditions.	(Arasu *et al*., 2022)
6	Datura species	Alkaloids, tannins	*Bacillus subtilis, Escherichia coli*	Direct antimicrobial activity confirmed by zone-of-inhibition assay	(Gachande & Khillare, 2013)
7	Garlic clove extract	Allicin	*Xanthomonas oryzae pv. oryzae (BLB in Rice)*	Direct antibacterial growth inhibition	(Srinivas *et al*.,2024)
8	*Panax ginseng* (Root extracts)	Ginsenosides (Triterpenoid saponins)	*Pseudomonas syringae pv. tomato*	Induction of PgSTS expression against bacteria	(Yoon *et al*., 2016)

9	*Vernonia cinerea*	Rutin, Methanone	*Xanthomonas oryzae pv oryzae*	The compounds interfere with PDF and Ddl enzyme activity, resulting in the suppression of Xoo growth	(Joshi *et al*., 2021)

Medicinal plants used to treat viral infections:

Crop losses in global level are estimated at roughly 20–30% each year in dietary staples like potatoes, rice, wheat, and maize. These losses are not only for the crops, it threatens the food security (Savary *et al*., 2019). About 50% of plant diseases are caused by plant viruses, which are extremely deadly plant pathogens that seriously jeopardise food security and the global economy (He & Krainer, 2020; Savary *et al*., 2019). Chemical control of plant viruses has been one of the key elements of integrated disease management techniques. Since direct control methods are typically ineffective against viruses, insecticides are specially used for their ease of application and efficiency in stopping virus transmission by vectors (Garzo *et al*., 2020). However, the usage of chemicals leads to environmental ineffectiveness and health risks (Pandit *et al*., 2022). The bioactive compounds produced from the plants help to control the viral infections through various mechanisms, such as the building up of an immune response in plants, blocking of viral replication, or directly inhibiting the virus particles (Thomas *et al*., 2021). The bioactive compounds from green tea, caffeine and catechin, have binding affinities for Banana Bunchy Top Virus (BBTV) proteins (DNA-R, DNA-U3, DNA-S, DNA-M, DNA-C, and DNA-N) through molecular docking analysis, thereby reducing the virus's virulence (Abdel *et al*., 2025). The detailed antiviral activity of antipathogenic compounds is described in Table 4.

Table 4. Antipathogenic compounds extracted from medicinal plants and their viral targets exhibit antiviral action

S. No	Medicinal plant extracts	Bioactive compounds	Target viral Plant pathogens	Mechanism	Reference
1	*Mirabilis jalapa* (roots)	Mirabilis Antiviral Protein (MAP)	*Tobacco mosaic virus* (TMV) — related tobamovirus to ToMV	MAP, a type-I ribosome-inactivating protein, removes a specific adenine from host rRNA, halting protein synthesis and thereby suppressing viral replication.	(Nishida *et al*., 2025)
2	Rosemary (*Salvia rosmarinus*, syn. *Rosmarinus officinalis*) essential oil	α-Terpineol, isoborneol, camphor	*Tobacco mosaic virus (*TMV) — *Nicotiana glutinosa*	Inhibits viral infection by directly inactivating virions and disrupting coat protein formation, thereby impairing host adsorption and entry.	(Al-Askar *et al*., 2025)
3	Thyme (*Thyme vulgaris*) essential oil	Thymol	*Cucumber mosaic virus* (CMV)- *Chenopodium quinoa*	Confers resistance to CMV infection following pre-inoculation application.	(Paduch-Cichal *et al*., 2022)
4	Oregano (*Origanum vulgare*) essential oil	Carvacrol	*Cucumber mosaic virus* (CMV)- *Chenopodium quinoa*	Restricts infection, with the impact determined by the timing of treatment.	(Paduch-Cichal *et al*., 2022)
5	*Chenopodium quinoa*	High saponin content	*Cucumber mosaic virus*	Upregulation of TSARL1 promotes saponin biosynthesis and localizes CMV infection, while ROS-mediated hypersensitive response, programmed cell death, and miRNA/siRNA silencing restrict viral spread.	(Soltani *et al*., 2021)
6	*Alpinia zerumbet* aqueous extracts	Proanthocyanidins	*Tomato mosaic virus* (ToMV*)*- *Nicotiana*	Direct viral inactivation by proanthocyanidins (PACs), resulting in	(Narusaka *et al*., 2020)

			benthamiana, Tomato	reduced ToMV infectivity and infection.	
7	*Ammi visnaga*	Furanochromones	*Tomato mosaic virus (*ToMV)- Datura metal host	Activates systemic plant defense by upregulating defense-related genes, including SbWRKY transcription factors, thereby enhancing resistance to TMV infection.	(Aseel *et al*., 2024)

Integration with Biocontrol agents:
A multi-layered defence system is created when plant-derived antipathogenic compounds are combined with beneficial microorganisms like *Pseudomonas fluorescens*, *Bacillus subtilis*, and *Trichoderma* spp. Mycoparasitism, antibiosis, competition, and the generation of systemic resistance are some of the ways in which these bacteria contribute (Calefi *et al*., 2025). However, some phenolics and flavonoids, such chitinases and β-1,3-glucanases, can promote microbial growth and enzymatic activity. Sublethal concentrations of plant extracts may weaken pathogen structures, making them more susceptible to microbial attack (Lyubenova *et al*., 2023).

Integration with Synthetic chemicals:
Combining synthetic fungicides with antipathogenic compounds generated from plants provides a workable way to lower chemical inputs without sacrificing effectiveness. By making pathogen membranes more permeable, allowing for increased chemical uptake, and preventing pathogens' detoxification processes, plant metabolites can improve the effectiveness of pesticides. Research has demonstrated that plant extracts such as *Azadirachta indica*, *Allium sativum*, *Zingiber officinale*, and *Eucalyptus* spp. exhibit synergistic activity against pathogens like *Fusarium*, *Alternaria*, and *Colletotrichum* when combined with reduced doses of fungicides like carbendazim, tebuconazole, and propiconazole. Neem-based extracts enhanced the suppression of wilt and leaf spot infections in vegetables while lowering chemical residues when coupled with fungicides (Atri *et al*., 2024).

Comparative evaluation of *in vitro*, greenhouse and field efficacy of plant-derived antipathogenic products against crop diseases:
Plant-derived antipathogenic products have demonstrated considerable potential for suppressing a wide range of phytopathogens under controlled *in vitro* conditions. However, their performance may differ substantially under greenhouse and field conditions due to variations in application dose, formulation, treatment frequency, environmental factors, pathogen pressure and plant-pathogen interactions. Therefore, evaluating their efficacy across different experimental scales is essential for determining whether laboratory level activity can translate into consistent disease management under practical agricultural conditions. Comparative assessment also helps identify compounds or formulations that show reliable disease suppression and potential agronomic benefits beyond pathogen inhibition. Table 5 summarizes the available *in vitro*, greenhouse, and field evidence, including the crop, target pathogen, plant-derived product or compound, application dose, treatment frequency, disease reduction, and yield response, where reported.

Table 5: Comparative Evaluation of *In Vitro*, Greenhouse, and Field Efficacy of Plant-Derived Antipathogenic Products Against Crop Diseases

S. No	Botanicals	Level of Experimental Validation	Crop/Pathogen	Dose/Concentration	Frequency of application	Disease reduction	Yield/Growth response	Reference
1	*Azadirachta indica* and *Lippia javanica* water extracts	*In vitro*, greenhouse, field	Common bean / anthracnose (*Colletotrichum boninense*)	10% w/v in field	Inoculated after emergence, then sprayed 7 days later	In *In vitro*100% inhibition of fungal growth and 75–100% inhibition of spore germination, whereas field disease control was evident but lower than that observed under screenhouse conditions	Seed yield increased by 350 kg ha⁻¹, corresponding to an overall 10–15% increase compared with the untreated control	(Kushaha *et al.,* 2024)
2	Garlic, onion, and neem extracts; compared with bioagents and fungicide	*In vitro*, greenhouse, field	Bean / damping-off and root rot (*Rhizoctonia solani*)	Garlic and onion most effective at 5% and 7%	Seed treatment was practiced	All extracts inhibited pathogen growth *in vitro* and reduced disease under greenhouse and field conditions, although neem extract showed comparatively lower efficacy.	Compare to control it improved the plant growth, survival and yield.	(Khalifa *et al.,* 2021)
3	Clove (*Syzygium aromaticum*) essential oil	*In vitro*, greenhouse, field (2 seasons)	Marigold Root rot complex (*Fusarium solani, F. oxysporum, Rhizoctonia solani, Sclerotinia sclerotiorum*)	In vitro: 1 mL/L; Greenhouse & field: 3 mL/L seed soak (12 h) + 1.5 mL/L foliar spray	One pre-sowing seed soak followed by three foliar sprays at 7-day intervals, beginning at the 2–4 true-leaf stage.	*In vitro* mycelial inhibition reached 100% against *F. solani*, while field treatments reduced root rot to 8.3% and wilt to	Plant height increased to 87.2 cm vs. 47.3 cm in the control, with higher fresh inflorescence weight and	(Ahmed *et al.,* 2023)

						16.4%, representing approximately 74–81% disease reduction compared with untreated controls.	increased chlorophyll, phenolics, catalase (CAT), ascorbate peroxidase (APX), and superoxide dismutase (SOD) activities.	
4	Combined aqueous extracts of *Mentha piperita* + *Azadirachta indica* + *Citrus limon*	*In vitro* (poison food & disk diffusion), Glasshouse, Field (3 rice cultivars)	Rice (*Oryza sativa*, cvs. Basmati Super, IRRI-24, TN-1) / Bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae*)	A 50% decoction concentration, selected as the most effective *in vitro* dose, was subsequently evaluated under glasshouse and field conditions.	4 foliar has been done at 15 days intervals	Disease severity was reduced by 83.0–84.4% across the three cultivars, representing the highest efficacy among all treatments evaluated.	IRRI-24 produced the highest paddy yield (6.33–6.66 t ha^{-1}) among the botanical treatments, with significant improvements in tiller number, panicle length, and 500-grain weight compared with the control.	(Naqvi, 2019)
5	*Bougainvillea spectabilis* leaf extract	Greenhouse	*Papaya ringspot virus* (PRSV)	10% leaf extract, applied as combined foliar spray + soil drench	Treatments were applied repeatedly throughout the experimental period.	Disease severity was reduced to 6.67%, the lowest among treatments, with a significant decrease in viral titre in leaf tissue after the final application.	Plant height and stem girth were superior to the control, with the highest leaf chlorophyll content (44.67 Soil Plant Analysis Development units) among all treatments.	(Harish & Cherian, 2019)
6	Citrus-derived botanical insecticide, d-limonene	Field (pot-grown plants under field/outdoor conditions	*Papaya leaf curl* (Red queen RQ, Red top RT variety) (begomovirus complex	5% d-limonene foliar spray	Four sprays were applied at 30-day intervals over	Disease incidence decreased to 39.88% at 105 days after treatment	Treatments produced the highest flower (8.67 in RQ; 10.67 in RT) and	(Hossain *et al.*, 2023)

			including *Tomato leaf curl Bangladesh virus*)		approximately 105 days.	(DAT) in 'Red Queen' variety compared with 96.30% in the control, with the lowest disease severity recorded at several assessment points.	fruit counts (6.67 in RQ; 6 in RT), compared with no fruits in the control, along with increased plant height.	

use of compounds obtained from medicinal plants in plant disease management is often limited by variability in phytochemical composition caused by differences in genotype, geographical origin, environmental conditions and extraction methods, leading to inconsistent bioactivity and poor reproducibility under field conditions (Nandhini *et al*., 2026). The stability and effectiveness of these bioactive chemicals are further diminished by environmental elements as temperature, UV radiation, precipitation, and soil interactions. Despite these challenges, commercialization of botanical pesticides is gradually increasing, with products comes from plants such as *Azadirachta indica*, *Allium sativum*, jojoba and rosemary being marketed as eco-friendly formulations including emulsifiable concentrates and wettable powders (Suteu *et al*., 2020). Many medicinal and aromatic plants, particularly those attached to the Lamiaceae family, possess strong antimicrobial activity against soil-borne pathogens; however, issues related to high production cost, inconsistent field performance and regulatory barriers still restrict large-scale adoption (Greff *et al*., 2023). Recent advances such as nano-thymol oil-in-water microemulsions derived from *Botrytis cinerea* mycelial growth and conidial germination have been effectively inhibited by Thymus vulgaris, highlighting the potential of advanced botanical formulations for sustainable crop protection. The commercial usage of eco-friendly fungicides is detailed in Table 6.

Table 6. Commercially registered and experimental plant-derived formulations for the management of crop diseases: active ingredients, product status, target pathogens, and modes of action.

S. No	Medicinal Plant	Commercial formulation	Experimental formulation	Active ingredient/Type of emulsion	Product status/Registered markets	Crop/Pathogen	Mode of action	Reference
1	*Reynoutria sachalinensis*	Regalia® Maxx / Regalia®	Regalia SC / ethanolic R. sachalinensis extract used experimentally	R. sachalinensis extract; SC (suspension concentrate)	Registered commercial biofungicide; current registrations documented in Canada; also marketed/registered in several other countries	Grape – powdery mildew (*Erysiphe/Uncinula necator*); cucurbits - powdery mildew; hops - downy mildew; other fruit/vegetable crops	Induces systemic resistance, enhancing papilla and callose deposition, cell-wall reinforcement, and plant defense responses.	(Greff *et al*., 2023)
2	*Azadirachta indica* (neem)	NeemAzal®-T/S; NeemAzal®-F	Neem seed/kernel extracts and azadirachtin formulations	Azadirachtin; aqueous/EC-type botanical formulation depending on product	Registered commercial botanical insecticide; NeemAzal products are registered under CIB&RC in India; NeemAzal-T/S is also authorized in European agriculture	Tomato – *Alternaria solani*	Membrane disruption and fungal growth inhibition	(Kilani-Morakchi *et al*., 2021)
3	*Melaleuca alternifolia* (tea tree)	Timorex® Gold	Tea tree - oil formulations	Approx 23.8% - EC (emulsifiable concentrate)	Registered commercial botanical fungicide; registration documented in Australia and Canada	Tomato, pepper, cucumber, grape, strawberry, cucurbits - powdery mildew; grape – downy mildew/*Botrytis*	Disruption of fungal membrane integrity, causing increased permeability and cellular damage.	(Reuveni *et al*., 2020)
4	*Cinnamomum* spp	Cinnerate®	Cinnamon essential-oil formulations	Cinnamon oil rich in cinnamaldehyde; high-essential-oil botanical formulation	Commercially registered in selected U.S. states	Fruit, vegetable and specialty crops – Powdery mildew, *Botrytis*, rust and other fungal diseases.	Membrane disruption, inhibition of cellular growth and dehydration of pathogen cells.	(Yursida *et al*., 2025)
5	*Thymus* spp (Thyme)	Thyme oil 26% LC	Microencapsulated thyme – oil formulations	Thyme oil 26%; microencapsulated liquid concentrate	Registered pesticide product in the USA; EPA Reg. No. 99869-2	Fungal and Bacterial plant pathogens.	Inhibits fungal cell division and replication	(U.S. Environmental Protection Agency, 2025)

Safety, Phytotoxicity, and Ecotoxicological Considerations of Medicinal Plant-Derived Antipathogenic Products:

Plant-derived antipathogenic products are increasingly considered alternatives to synthetic pesticides because several phytochemicals exhibit rapid environmental degradation and relatively low persistence. For example, cumic acid from Cuminum cyminum showed short soil half-lives of approximately 4–5 days and relatively low toxicity toward several tested non-target organisms, although moderate toxicity to bees and quails was also observed (Yue *et al*., 2024). However, botanical origin alone does not guarantee environmental safety. Experimental studies indicate that the effects of plant-derived products can vary according to concentration, exposure conditions and formulation; for instance, Plantago major and Sambucus nigra extracts produced concentration-dependent effects on tomato seed germination (Lam-Gutiérrez *et al*., 2025). Similarly, a nanoclay formulation containing *Satureja montana* essential oil produced measurable effects on aquatic organisms and reduced reproduction of the soil collembolan *Folsomia candida*, demonstrating that formulation can influence non-target toxicity (Machado *et al*., 2025). Moreover, recent literature indicates that ecotoxicological information on botanical pesticides remains insufficient, particularly regarding non-target organisms and nano-formulations (Soares *et al*., 2026). Therefore, the environmental safety of plant-derived antipathogenic products should be demonstrated experimentally rather than inferred from their natural origin, with specific evaluation of crop phytotoxicity, pollinators, beneficial insects, soil microorganisms, aquatic organisms and formulation-dependent risks.

Challenges and Limitations:

The intrinsic heterogeneity of phytochemical content, which is impacted by elements including plant genotype, geographic origin, ambient circumstances, and extraction techniques, is one of the main limitations; this variability often leads to inconsistent bioactivity and complicates reproducibility across studies and field applications. Consequently, inconsistent field performance remains a critical concern, as efficacy observed under controlled laboratory conditions does not always translate reliably to diverse agro-ecological environments where factors such as temperature, UV exposure, rainfall, and soil dynamics can rapidly degrade active compounds and change their mode of action. Despite these constraints, the commercialization of botanical pesticides is steadily advancing. Plant-based products derived from species such as *Azadirachta indica* and *Allium sativum* are already available in formulations including emulsifiable concentrates and wettable powders, demonstrating their potential as eco-friendly alternatives to synthetic pesticides. Nevertheless, broader adoption is limited by regulatory challenges, variability in field performance and scalability concerns.

Advances and future perspectives:

Recent interdisciplinary advances are transforming the development of medicinal plant-derived antipathogenic compounds for phytopathogen management through precision-based and mechanism-driven approaches. Genomics and metabolomics help identify bioactive compounds and understand plant defense and metabolite biosynthesis pathways, enabling the selection of effective medicinal plants. Molecular docking and computational tools accelerate the identification of potent phytochemicals by predicting their interaction with pathogen targets. Formulations based on nanotechnology, like nanoparticles and nano-emulsions, enhance the phytochemicals' stability, solubility, and controlled distribution in field settings. Furthermore, data-driven methods facilitate the quick discovery of novel antimicrobial agents for long-term crop protection, while genome-editing and metabolic engineering technologies improve the synthesis and consistency of useful secondary metabolites.

Conclusion:

Medicinal plant-derived antipathogenic compounds represent a robust and sustainable alternative for the management of phytopathogens addressing key limitations associated with conventional synthetic agrochemicals. Their broad-spectrum efficacy against fungal, bacterial and viral pathogen is primarily driven by multitarget mechanisms, including membrane disruption, metabolic interference, inhibition of nucleic acid synthesis and activation of host defense pathway. Recent advances in formulation technologies, particularly nano-based delivery systems along with their integration with biological control agents and reduced chemical inputs have significantly enhanced their stability, bioavailability and field applicability. Despite these advancements, challenges such as variability in phytochemical composition, lack of standardization and inconsistent field performance continue to limit large-scale adoption. Addressing these constraints through interdisciplinary approaches including omics technologies precision formulation and rigorous field validation is essential for translating laboratory findings into practical applications.

Author contribution

Dhibendra Ashokkumar & Ushamalini Chinnaswamy: Conceptualised and prepared original draft, Vaikuntavasan Paranidharan: Reviewing and editing, Premalakshmi Velu: Reviewing, editing and visual representation, Radha Palaniswamy: Reviewing and Editing

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Ethical Approval
This study did not involve any experiments on humans or animals and therefore did not require ethical approval.
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All authors have read and approved the final manuscript and consent to its publication.

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