

REVIEW

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Postharvest management of fungal pathogens of selected fruits: role of plant extracts, essential oils, edible films/coatings, and green nanoparticles

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Abstract

Background Fruits such as mango (*Mangifera indica*), apple (*Malus × domestica*), tomato (*Solanum lycopersicum*), and strawberry (*Fragaria × ananassa*), are consumed worldwide and fall under a highly economical category of crops. In contrast, the postharvest management against fungal infections particularly remains a challenge for maintaining the quality standards of these fruits. For decades, farmers have been dependent upon synthetic fungicides, thus having a serious impact on human health as well as the overall ecosystem. In order to avoid such situations, diverse research laboratories around the world have discovered safe alternatives to these chemical fungicides.

Main body The current review aims to summarize as well as analyze the substitute postharvest treatments, including plant extracts, edible films/coatings, green metallic nanoparticles, and plant-based essential oils for controlling fungal infections. The review also highlights the challenges related to each methodology.

Conclusion Natural fungicides effectively kill or inhibit postharvest fungi in addition to maintaining the overall fruit quality that is of utmost importance for retailers, farmers, and ultimate consumers.

Keywords Fungal infections, Natural fungicides, Postharvest management, Safety

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1 Introduction

There has been a rise in the accessibility of energy-rich foods, resulting in the dietary changes of the population along with increase in the demand for use of sustainably grown products [1]. Hence, an increased demand for freshly produced fruits and vegetables has been noticed [1]. Fresh produce has been defined as “fresh fruits and vegetables that are likely to be sold to consumers in an unprocessed or minimally processed (i.e., raw) form” [2]. These fresh products are an abundant source of essential minerals and vitamins; however, they are also very perishable products having a short self-life and hence, generating piles of postharvest losses [3]. Apple i.e., *Malus × domestica* is a member of *Rosaceae* family, also known as pome fruit composing 2–5 carpels covered with a crunchy flesh [4]. Apple is amongst the topmost fruit crops cultivated in over 63 countries having diverse climatic zones such as the subtropical and temperate regions; however, commercial production is limited to less than 25° – 52° latitude [5]. Mango or *Mangifera indica* owns a pleasant aroma, unique flavor and contains an array of nutrients. The fruit is highly popular amongst its consumers and has steadily taken up the place of second most consumed and grown tropical fruit of the world [6]. The United Nations’ Food and Agriculture Organization (FAO) data of 2020 suggests that the worldwide mango production is nearly 54.83 million tons, with a planted area of more than 55 million hectares [7]. On the basis of FAO reports in 2021, the global production of strawberries i.e., *Fragaria × ananassa* had surpassed 9.18 Mt [8]. Asia is the leading continental producer with 4.53 Mt of production, followed by America at 2.18 Mt, with Europe at 1.76 Mt, followed by Africa at 634.29 Kt along with Oceania at 60.31 Kt [8]. There has been a historic increase in the production of strawberries. But the 2020 data show a 2% reduction in strawberry production as compared to the 2019 data. The reduction could be attributed to COVID-19 pandemic effects and the challenges associated with availability and cost of labour [8]. The tomatoes or *Solanum lycopersicum* consumption specifically, has been related to reduction in susceptibility to life-threatening ailments, such as cancer, heart disease, and diabetes among others [9]. Besides their health benefits, tomatoes have been the most grown vegetable of the world in 2022, produced at 186 Mt, thus representing an increment from 110 Mt as reported in the previous two decades [10].

Fruits are exported to long-distance markets through refrigerated sea shipments. The entire marketing timeline includes roughly 30 days until the fruit reaches its consumers [11]. Throughout transportation, refrigerated storage, and retail shelf life, fruits may undergo postharvest deterioration due to the activity of diverse microbial agents [11]. Amongst all the food products globally, fruits

evidence the maximum postharvest losses varying from 28% to 55% of their total production and also accounting for around 750 billion USD per annum [12, 13]. The extreme cases have witnessed postharvest fresh produce losses as high as 60% depending upon the type of produce [14]. Figure 1 exemplify the global article distribution about the “fruit postharvest losses” published in Web of Science (WOS); where China is stood first and USA, Spain and India subsequently.

Sivakumar and Bautista-Baños [15] published a review which highlights the necessity for development of a novel natural pesticide for replacing the application of synthetic pesticides at postharvest stage owing to higher pesticide residue levels in the edible parts of the fruit, effect of pesticides on the environmental footprint, and pathogens developing pesticide resistance. A major role has been played by “Farm to Fork Strategy” in the European Union’s European Green Deal aiming at reduced reliance on pesticides, enhancing organic farming and making available sustainable diets for benefiting consumers’ health, which will subsequently help in reduction of medical care expenditures for treasury funds [11]. Taking consideration of the above, the current review summarizes as well as analyzes recent advancements and trends in using alternative postharvest treatments in controlling fungal pathogens attacking fruit crops specifically for apple i.e., *Malus × domestica*, strawberries i.e., *Fragaria × ananassa*, tomatoes i.e., *Solanum lycopersicum*, and mango i.e., *Mangifera indica*. The foremost part of this review stresses on the postharvest fungal pathogen types, use of chemicals as well as their health implications. While the second part focuses on the role of plant-based essential oils, plant extracts, green metallic nanoparticles, and edible films/coatings in postharvest management of selected fruit crops. This review also throws light on the various challenges related to each method.

1.1 Methodology

Extensive academic literature search has been conducted for the preparation of this review by utilizing various major scientific databases. The authors have carried out comprehensive search through electronic platforms, such as Google Scholar, EBSCO, PubMed, Web of Science, and Scopus using a specific set of keywords. These keywords included “apple,” “mango,” “apple,” “strawberries,” “postharvest infections,” “chemical treatments,” “fungal infections,” “health concerns,” “essential oils,” “plant extracts,” “green metallic nanoparticles,” “edible coatings,” “edible films,” and “challenges.” Research/review articles were selected on the basis of following inclusion criteria: (a) research publications in English language as well as (b) strict compliance with a particular experimental study design. After removing the duplicate records, 61

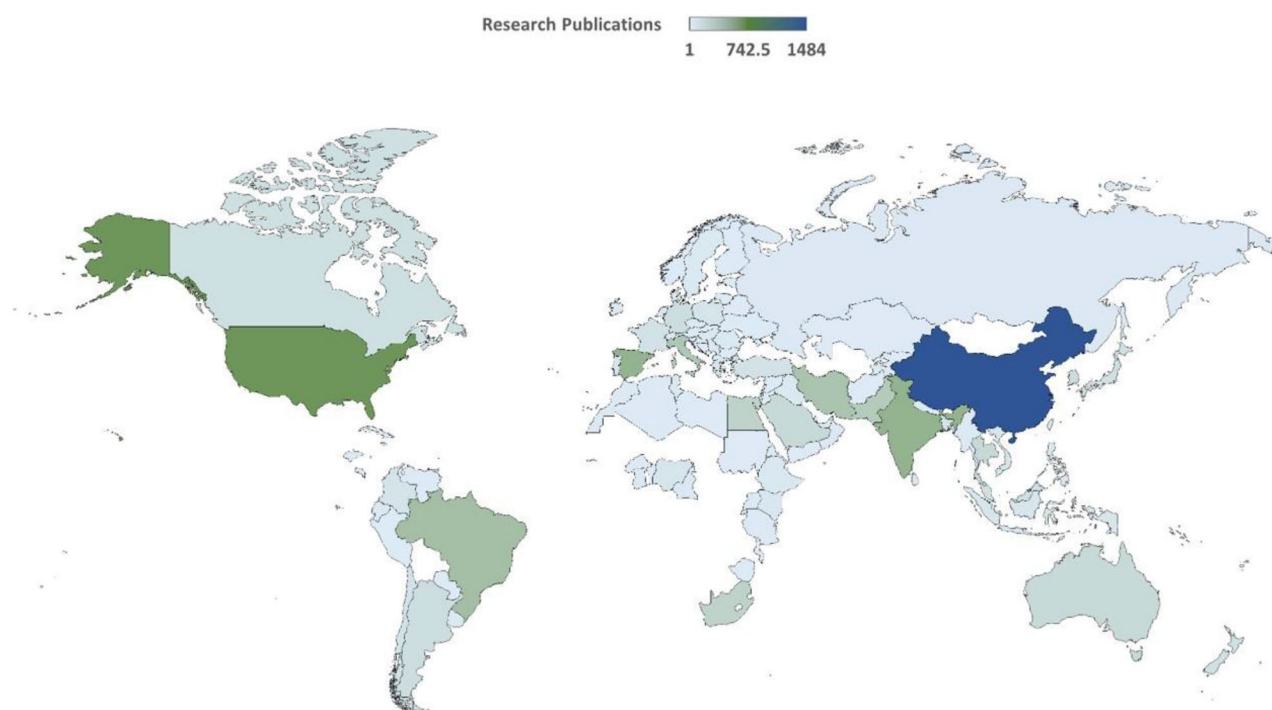


Fig. 1 Heatmap showing the number of publications indexed in Web of Science from 1 st January 1991 to 31 st December 2024 (only in English language) around the globe

publications met the already defined eligibility criteria and hence were incorporated in the analysis.

2 Type of fungal phytopathogens of the selected fruits: an overview

2.1 Apple

Apple bitter rot is a widespread disease affecting fruits, caused by fungus *Colletotrichum* spp. and occurring in most of the apple cultivating countries [16]. Infections caused by *Colletotrichum acutatum* species complex (SC) on European apples are commonly reported with rising number of reports from Belgium, Italy, France, England, Slovenia and Norway recently [17]. Studies from Sweden and Germany describe postharvest fruit losses of 25 and 10%, respectively, caused by *Colletotrichum acutatum* species complex [18, 19]. Bull's eye rot disease of apple is also an important postharvest infection, occurring in North America, Australia, Europe and Chile, the major fruit-growing areas [17]. The disease usually occurs in most of the apple cultivars, having an incidence between 10 and 20%, which may exceed 40% in years which are favourable for pathogen infection [20, 21]. 'Golden Delicious' and quite a few late maturing cultivars of apple, including Pink Lady, are predominantly susceptible to this disease in Europe [21, 22]. Bull's eye lesions appearance on apples is generally attributed to *Neofabraea* sps, with *Neofabraea vagabunda* (syn. *Neofabraea alba*) being the main causative agent.

Penicillium expansum causes blue mold disease, one of the prevalent and economically expensive postharvest fruit decay infections in the world [23]. *Alternaria alternata* causes black spot rot disease, which is currently a major postharvest apple fruit disease in China that infects and colonizes through wounds present on the apple surface during its storage [24]. These postharvest pathogenic fungi not only critically limit the fruits' commercial value, but also conveniently produce mycotoxins that harm humans [25, 26].

2.2 Mango

Postharvest mango diseases include stem-end rot caused by *Lasioidiploidia theobromae*, anthracnose by *Colletotrichum gloeosporioides*, *Diplodia* stem-end rot disease by *Diplodia natalensis*, brown spot disease by *Pestalotiopsis mangiferae*, black spot rot disease by *Phomopsis mangiferae* and black mold rot disease by *Aspergillus niger*, and black mold rot disease by *A. niger* [27]. It has been estimated that 30% of the postharvest mango fruit losses are caused by *Colletotrichum* infection. The *Aspergillus* species *fumigates*, *Aspergillus niger*, and *flavus* cause postharvest losses up to 10% [28].

2.3 Strawberries

The most common rot found amongst strawberries is the gray mold disease caused by the necrotrophic fungus, *Botrytis cinerea* [29]. Soft rot or *Mucor* rot or *Rhizopus*

rot, is caused by *Rhizopus* and *Mucor* genera, another plant pathogenic fungi commonly associated with post-harvest storage of strawberry [30]. Anthracnose is common infection caused by *Colletotrichum* spp., specifically *Colletotrichum acutatum* [30].

2.4 Tomato

Fungal infections causing high decrease in tomato quantity and quality include *Alternaria solani*, *Alternaria alternata*, *Fusarium oxysporum*, *Sclerotium rolfsii*, *Geotrichum candidum*, *Verticillium dahlia*, and *Septoria lycopersici* [31].

3 Chemicals used in the postharvest management of selected fruits

3.1 Apple

1-Methylcyclopropene (1-MCP) fall amongst the commonest synthetic chemicals used extensively in apple industry throughout the world in combination with diverse storage conditions for extension of storability and ensure year-round fruit availability in local as well as high-end markets. It significantly delays senescence and ripening by reducing rate of respiration and production of ethylene in apples while being stored. Nonetheless, 1-MCP application and response significantly depend upon apple cultivar under treatment, concentration, coupling storage type, temperature conditions, and treatment duration [32]. Hasan et al. [4] have discovered 2 new ethylene antagonists, namely 1*H*-cyclopropa[b]naphthalene (BC) and 1*H*-cyclopropabenzene (NC). These have a chemical structure different from 1-MCP, but have similar function, and have been tested as fumigation and dip for delaying ripening as well as maintenance of postharvest fresh horticultural produce quality during storage. The postharvest application of dip and fumigation treatment of BC and NC compounds significantly downregulated respiration rate and ethylene production, maintained higher firmness, reduced water loss along with and total phenolic content in apple fruits. BC and NC compounds performed well during apple storage on application as fumigation treatment in contrast to liquid formulation having better stability under room conditions [33].

In 2016, the fungicide difenoconazole (DIF) which is a demethylation inhibitor (DMI) in combination with fludioxonil was registered as Academy™ (with Syngenta Crop Protection) and was used for managing post-harvest diseases in pome fruits. DIF or Inspire Super (marketed by Syngenta Crop Protection), has also been sprayed in orchards for combating apple powdery mildew disease as well as other preharvest diseases [34]. DIF, when applied alone or combined with other fungicides, demonstrated efficacy against different pathogens, including *Venturia inaequalis*, *Penicillium expansum*,

Podosphaera leucotricha, *Colletotrichum fructicola*, and *Alternaria alternata* [34]. The DMIs primarily act by targeting the enzyme 14 α - demethylase, encoded by CYP51 gene and hence is essential for ergosterol biosynthesis [34]. Fludioxonil fungicide is chemically a phenylpyrrole which inhibits spore germination, elongation of germ-tube, and fungal mycelial growth whereas pyrimethanil has a reduced-risk and broad-spectrum fungicide inhibiting germ-tube elongation as well as mycelial growth [35]. These fungicides are ideal partners for resistance management as they have diverse codes for Fungicide Resistance Action Committee (FRAC) [36]. Both of these fungicides are capable of controlling *Phlyctema* and *Neofabraea* sps. resulting in bull's eye rot disease on pome fruit on application as postharvest treatments in USA and Chile [36]. In South Africa, these fungicides have been registered for postharvest application on the pome fruit [36]. In spite of the availability of various fungicides, currently there are no registered fungicides specifically for the control of bull's eye rot. Diphenylamine (DPA) is an organic liposoluble antioxidant used in the form of solutions effectively used in controlling postharvest disorders (such as storage scald disease in vegetables and fruits), before its usage ban in several countries [37]. DPA finds its wide use in prevention of the postharvest deterioration of pears and apples and vegetable crops, caused by superficial scald. The anti-scald activity of DPA is directly linked to its antioxidant properties, thus preventing the oxidation of horticultural products during storage [38]. However, the DPA mechanisms of action in reduction of superficial scald disease are not yet entirely understood, and remain inconsistent amongst different authors [39]. While the most prevalent hypothesis involves action of DPA as an antioxidant along with inhibition of α -farnesene oxidation to conjugated trienols (CTs) [38, 40].

3.2 Mango

Recent studies have also revealed that 1-MCP at a dose of 1 μ L/L, and given for 12 h decreased ethylene production as well as rate of respiration in 'Kensington Pride' variety of mango fruit after a storage period of 16 days at ambient temperature [41]. Studies from another research group showed that 1-MCP at a dose of 652 μ g/L, and given for 5 min diminished the total soluble solids (TSS) accumulation in 'Kent' mangoes on storage at 12 °C [42]. Hong et al. [43] have showed that treatment of 'Zill' variety of mango with 100 μ M nitric oxide (NO) for 30 min brought significant reduction in ethylene production and also delayed climacteric peak. Likewise, a reduced rate of respiration has been reported with 'Kensington Pride' mango fruit fumigated with 20 μ L/L NO for 2 h and after storage for seven days at 13 °C [44]. Authors also found that the mechanism of action for NO is related to its capability of binding to

1-aminocyclopropane-1-carboxylate oxidase (ACO) which further forms the ACO-NO binary complex [44].

A plant hormone, salicylic acid (SA) regulates a variety of plant physiological processes [45]. These physiological processes include chilling injury (CI) tolerance, postharvest disease resistance, and fruit ripening [46, 47]. SA is known for controlling anthracnose disease in mango fruit which is caused by fungi, *Colletotrichum gloeosporioides*. Zeng et al. [48] have reported that treatment of 'Matsu' mango with 1 mmol/L SA reduced the incidence of disease and lesion diameter of *Colletotrichum gloeosporioides*. In vitro study by He et al. [45] has revealed significant reduction in mycelial growth by treatment with SA (2 and 5 mM) in 'Tainong' mangoes. The researchers also found that SA at 2 mM concentration increased the enzymatic activities of β -1,3-Glucanase (GLU) and chitinase (CHI). The two enzymes help in inducing resistance towards diseases. GLU is documented to induce disease resistance at early stages of ripening of fruits [48].

Prochloraz, an imidazole fungicide was introduced in the year 1973. It acts by inhibition of lanosterol 14 α -demethylase (CYP51A1) enzyme, essential for fungal ergosterol production and is considered as an endocrine disruptor [49, 50]. Lately, the European Union has banned prochloraz usage. However, the lack of alternatives has facilitated its approval extension to 2021 [51]. Hence, alternative ways of controlling the postharvest decay need to be explored. Commercial dipping of mangoes in prochloraz fungicide has been reported to be effective in controlling anthracnose postharvest decay [51]. Sodium hypochlorite (NaOCl) solution can be prepared by combining chlorine with sodium hydroxide [52]. Post-harvest treatment of mango fruit with NaOCl could prevent contamination with fungus and increase their storage life [53].

3.3 Strawberries

Several studies have documented that hydrogen sulfide (H_2S) has scavenging action on reactive oxygen species (ROS) by promoting antioxidant enzymes as well as providing chilling resistance via induction of polyphenol compounds and proline [54]. Hydrogen sulfide is a gaseous molecule involved in signaling plant growth, postharvest ripening, senescence, and defense responses [55]. Sun et al. [56] have revealed the role of hydrogen sulfide in delaying the process of ripening in strawberries. The researchers treated strawberries with varying sodium hydrosulfide (NaHS) (H_2S donor) concentrations, stored the strawberries in a box maintained at 22 °C and having relative humidity (RH) of 70%, and studied the changes in quality for 48 h. It was observed that NaHS treatment at 1.5 M delayed the ripening process in white strawberries after harvesting and reduced their rate of respiration, thereby suppressing production of ethylene. Additionally,

the nutritional quality and appearance of the strawberries was intact even after 48 h, in contrast to the control group. Many researchers have analysed the impact of 1-MCP treated strawberries on their postharvest shelf life. Priyadarshi et al. [57] has treated fresh strawberries using various 1-MCP solution concentrations ranging from 0 to 1 μ L/L at 25 °C for 12 h and further stored them at 5 °C temperature and 95% RH. They observed that the fruits undergoing treatment with 1-MCP at 1 μ L/L maintained firmness and color even after storing them for 12 days. Furthermore, the rate of decay was lower in comparison to the control ones. In another study by Silva et al. [58] attempts have been made to identify the cause of delayed firmness in strawberries treated with 1-MCP. It was observed that treatment of strawberries with 100 nL/L 1-MCP for 2 h significantly suppressed the activities of cell wall-degrading enzymes, polygalacturonase (PG) and pectin methylesterase (PME).

Treatment with ethanol vapor has also been used for postharvest preservation of quality in strawberries. Priyadarshi et al. [57] have reviewed the use of polyethylene (PE) bags for packing strawberries and further treated them with various concentrations of ethanol vapors worked as a sustained release formulation. The bags were kept under storage at 20 °C. The quality of fruit was analyzed for a period of 7 days. The treatment with ethanol vapor effectively maintained the quality characteristics of strawberries over time, in contrast to the control ones. The treated strawberries showed better microbiological quality, decreased ethylene production, and slower respiration rate, thus resulting in diminished texture moisture content variations and titrable acidity observed over 7 days [57].

3.4 Tomato

The application of various disinfectants for postharvest tomato treatment has been well documented. For example, NaOCl solution has been utilized to sterilise tomatoes to reduce fungal infection incidence before application of any postharvest treatment [59]. Dipping of tomatoes in thiabendazole solution diminished the fruit microbial load [60]. Workneh et al. [61] have indicated that dipping of tomatoes in anolyte water for disinfection not only decreased the fruit microbial loads but also maintained the superior quality of tomato fruits during storage. Both disinfection and hydrocooling can be used simultaneously to achieve reduction of excessive field heat along with decreased microbial infection all together. In postharvest tomato fruit treatment, particularly, 1-MCP has been found to show prolongation of the fruit shelf life by retaining its firmness and postponing both lycopene accumulation as well as external colour development [62]. In addition, the benefit of 1-MCP use in tomatoes is to prevent abscission in fruits traded on

the vine [63]. Consequently, this will produce a desirable effect on the photosynthesis in vegetative tissues thereby, resulting in uninterrupted supply of some vital nutrients or substances to the fruit which further increases the consumption quality. Training and educating handlers on the use of 1-MCP in tomato fruits will help diminish postharvest loss related with the crop to a certain extent.

In tomato fruits, the treatment with calcium chloride (CaCl_2) is vital for maintenance of fruit quality by decreasing the physiological disorders, enhancing fruit firmness, prolonging shelf life, and delaying ripening process [64]. CaCl_2 has been documented to cause delay in tomato fruit colour development and slowing down the ethylene production thus extending fruit shelf life by 92% [65].

4 Health aspects of chemicals used in postharvest management of selected fruits

Limited toxicological data set has been submitted for 1-methylcyclopropene (1-MCP) [66]. No chronic or carcinogenic studies were available, along with testing of limited species in teratology and short-term studies [66]. Taking in consideration the finding of the existing toxicity studies, it was decided that the representative applications of 1-MCP as well as the physical characteristics of its active substance (a highly reactive gaseous compound) from the limited available data set was deemed acceptable. The acute toxicity studies conducted with the fabricated intermediate powder (alpha-cyclodextrin in complex with 4.5% 1-MCP in Manufacturing Use Product High Active Ingredient Powder (MUP-HAIP) or with the gas (through inhalation), with limited toxic effects being evidenced and it could be concluded that classification for acute dermal/inhalation/oral routes, eye or skin irritation or sensitisation of skin is not required for 1-MCP to a maximal mass content of around 5% as described in the classification, labelling and packaging (CLP) regulation [66]. The short-term oral toxicity analysis (with MUP-HAIP) conducted on rats and dogs displayed similar adverse effects, whereas the dogs showed more sensitivity with a 4.1 mg/Kg body weight per day of no observed adverse effect level (NOAEL), based on clinical chemistry and haematology changes, along with histopathological effects exerted on the liver, epididymides and testes in 90-day oral period of the study. In a 90-day study on rats by 1-MCP gaseous inhalation, 23.5 ppm of no-observed-adverse-effect concentration (NOAEC) (equivalent to 6.5 mg/Kg b.w/day of average systemic NOAEL, and with an assumption of 100% inhalation absorption) depending on the histopathological effects in spleen (haemosiderosis) and kidney (hyaline droplets) in males [66].

The difenoconazole residue has currently been detected in food as well as environmental matrices. The

concentration of DIF residues was about 4.74 mg/Kg at the preharvest intervals in fruits and vegetables under field conditions [67–69]. Also, it was regularly monitored in the marketed fruits and vegetables having 8.0–40.3% detectable rate and residual concentration reaching 1.90 mg/Kg, greater than the maximal residue limit in kumquat, brinjal, and cowpea [70, 71]. Although DIF had an acceptable dietary risk, it posed potential health hazards in Chinese consumers, having risk quotients between 2.44% and 84.1% [67–69]. Besides, DIF poses a greater ecological risk amongst aquatic ecosystems having risk quotients as high as 9525 [72]. Therefore, clarifying DIF'S toxicological effects and its mechanisms of actions is crucial to have a comprehensive understanding of its health and environmental hazards. Fludioxonil, derived from the antibiotic pyrrolnitrin, is authorized fungicide for utilization in more than 900 agricultural products [73]. The widespread use as well as persistent nature of fludioxonil have resulted in its presence in different organisms and environmental matrices [73]. In fact, higher concentrations of fludioxonil have previously been detected in the vineyard areas and agricultural soils along with indoor dust of the farmworker households across Argentina and Europe, as found in a recent research [73]. Additionally, fludioxonil has been identified as a human endocrine disruptor, while it also adversely affects numerous organisms [74]. Oxidative stresses caused by the production of reactive oxygen species (ROS) along with mitochondrial dysfunction have previously been proven as the modes of action for fludioxonil [75]. The WHO classifies fludioxonil as moderately hazardous chemical, while it is considered toxic as per the European classification, intoxicating aquatic life, meanwhile various studies demonstrate its harmful impact on various organisms including zebrafish (*Danio rerio*) and *Rhinella arenarum* [76].

Batterman et al. [77] have reviewed that chronic exposure to hydrogen sulphide at levels less than 10 ppm owes long association with odor aversion, nasal, respiratory, ocular, and neurological effects. Nonetheless, exposure to very low levels of H_2S , less than 0.03 ppm (or 30 ppb), is associated with enhanced neurological effects prevalence, and increments less than 0.001 ppm (or 1 ppb) in the H_2S concentrations have association with ocular, respiratory, and nasal effects. Many epidemiological literature studies are limited by co-pollutant exposures, exposure measurement error, and small sample size, potential confounding, and concerns over representativeness, and these studies are awaited for considering vulnerable populations. Conversely, the process of chlorination poses chemical threat towards human health owing to by-products DBPs disinfection [78]. DBPs are formed when the precursors like organic matter (OM) are present [79]. These DBPs (haloacetic acids (HAAs), trihalomethanes (THM), etc.) are alarming since 1974 pertaining to their possible risk

of cancer to human health as well as other chronic/sub-chronic health effects including cardiac anomalies, still birth, pre-term delivery, and low birth weight [80].

5 Role of plants extracts in postharvest management of fungal pathogens of selected fruits

Figure 2 detailed about the mechanism of different plant-based materials against fungal pathogens. Plant extracts are derived through the extractive action carried out on a plant part or itself (mostly dry and ground), using a suitable solvent. These contain plant compounds solubilized through the solvent used [81]. In two separate studies, Gurjar and co-workers [82] as well as Proestos and Varzakas [83] found that plant tissues have the ability of synthesizing aromatic secondary metabolites, including, phenols, phenolic acids, flavones, flavonoids, flavonols, quinones, coumarins, and tannins and their use has been increased in various food industries as an additive. These natural extracts possess antioxidant and antimicrobial

properties [84]. A given set of plant species have efficiency against a specific class of pests due to the presence of specific chemicals in these species [85]. Botanical fungicides also contain secondary metabolites which are poisonous to cell membranes, walls of fungi, and organelles [85]. These metabolites aid in preventing spore germination, mycelium growth, germ tubes lengthening, delayed sporulation, and production of DNA, proteins, and critical enzymes [85]. Additionally, these bring about structural changes in mycelia and hypha, which prevent various fungi such as *Fusarium* spp. and *Aspergillus* spp. from production of toxic compounds like fumonisin and aflatoxin respectively. Consequently, the fungal infections caused by mycotoxin production are less pathogenic [86]. At present, various studies have evaluated and found out that plant extracts constitute to be an important agro-chemical source used for controlling various postharvest losses, including fungal diseases as displayed in Table 1 [87].

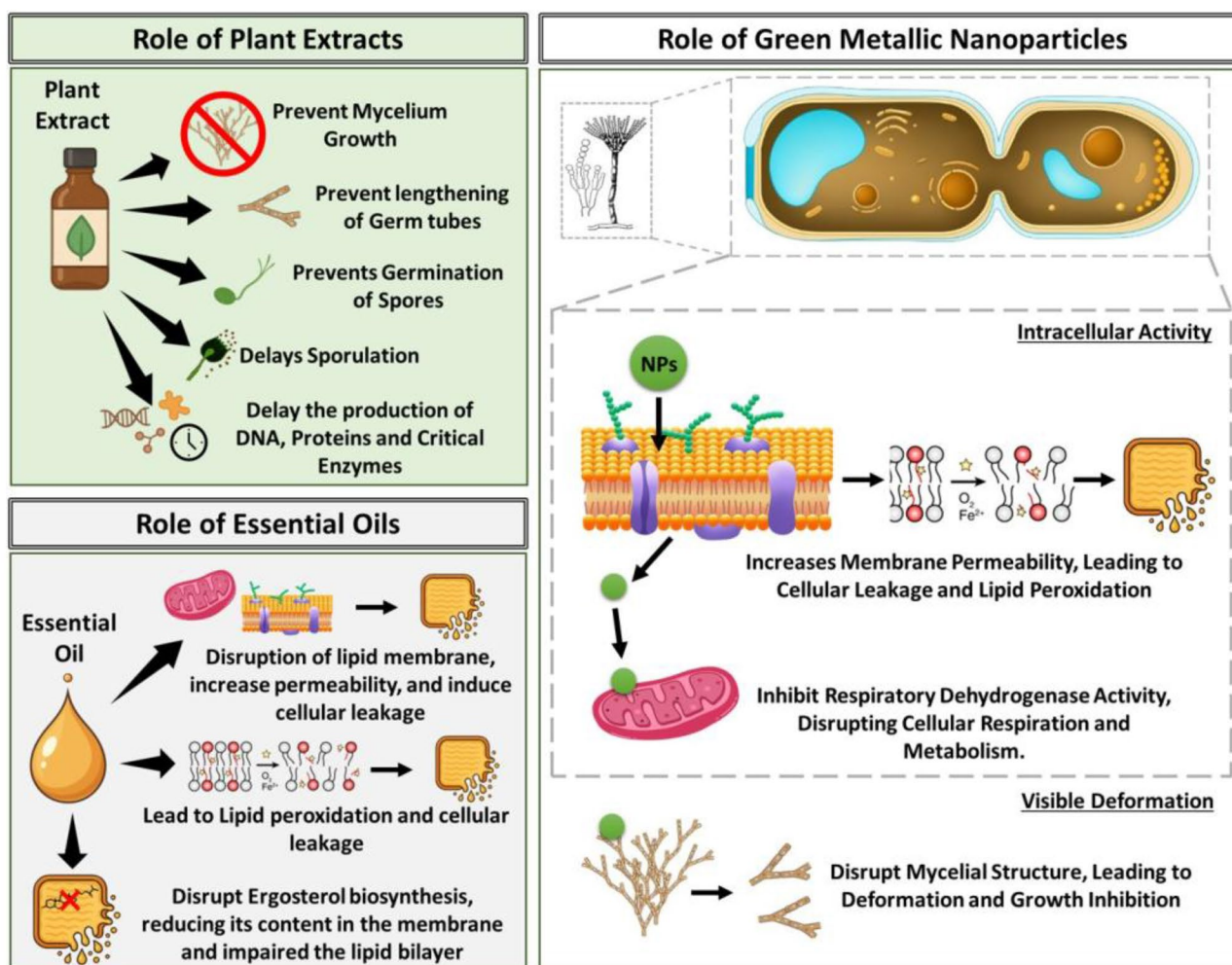


Fig. 2 Mechanism of action of various plant-derived materials against pathogenic fungi

Table 1 Effect of different plant extracts on postharvest fungi development on the four agricultural products

Plants/extract nature	Application on fruit	Protection against type of pathogens	Outcome	References
<i>Artemisia</i> , <i>Thymus vulgaris</i> , and <i>Cinnamomum camphora</i> / Aqueous, hexane, and alcohol	Apple	<i>Penicillium expansum</i> , and <i>Alternaria alternata</i>	Alcoholic and aqueous camphor extracts were found to be most effective in inhibition of fungal growth, with alcoholic wormwood extract in the follow up. This could be attributed to the potential of the active constituents in camphor extract for disrupting the cell membrane along with potentially releasing large molecules including proteins and nucleic acids into fungal cells	[88]
<i>Syzygium aromaticum</i> , <i>Eucalyptus globulus</i> , <i>Salvia officinalis</i> , and <i>Thymus vulgaris</i> L./ Aqueous	Apple	<i>Alternaria alternata</i> , <i>Botrytis cinerea</i> , and <i>Penicillium griseofulvum</i>	The clove extract completely inhibited all the selected pathogens on application at 20% concentration; Subsequently, the thyme extract inhibited <i>B. cinerea</i> growth completely at same concentration.; Eucalyptus extract showed lowest inhibition	[89]
<i>Cinnamomum cassia</i> (cinnamon), <i>Pimenta dioica</i> (pimento), and <i>Laurus nobilis</i> /ND	Apple	<i>Botrytis cinerea</i>	The cinnamon extract showed most effectiveness against gray mold in apple; However, higher extract concentrations were required for <i>Botrytis cinerea</i> inhibition efficiently in fruits under storage	[90]
<i>Zingiber officinale</i> / Aqueous	Mango	<i>Aspergillus niger</i> , and <i>Rhizopus stolonifer</i>	The <i>Z. officinale</i> extract at 50 and 100% w/v concentrations could inhibit the fungal radial growth significantly	[91]
<i>Allium sativum</i> / Aqueous	Mango	<i>Lasiodiplodia theobromae</i>	Healthy unripe mangoes were soaked in diverse concentrations of the garlic extract with different time periods; Fruit soaked for 4 h at 100% extract concentration prevented lesion development. Hence, it was concluded that the garlic extract was capable of suppressing <i>Lasiodiplodia theobromae</i> growth	[92]
<i>Carya illinoensis</i> , and <i>Arachis hypogaea</i> / Hexane, and methanol	Strawberries	<i>Botrytis cinerea</i>	Ex vivo assays on peanut (P) methanolic (MeOH) extracts (MeOH-P) decreased both disease severity and incidence which was comparable to the synthetic fungicidal agents	[93]
<i>Moringa oleifera</i> / Aqueous, methanol, methylene chloride, and petroleum ether	Strawberries	<i>Botrytis cinerea</i>	The methanolic extract exhibited most significant effectiveness towards grey mould	[94]
<i>Annona muricata</i> / Aqueous, and methanol	Tomato	<i>Alternaria. alternata</i>	<i>Annona muricata</i> extracts damaged the hyphal morphology and conidial structures significantly	[95]
<i>Moringa oleifera</i> / Aqueous, ethanol, and petroleum ether	Tomato	<i>Natrassia mangifera</i> , <i>Fusarium oxysporum</i> , <i>Aspergillus niger</i> , <i>Alternaria alternata</i> , and <i>Metarhizium anisoplae</i>	Irrespective of the type, all extracts inhibited all microbial growth to varying degrees, in different concentrations, barring petroleum ether extract	[96]

ND = not defined

5.1 Apple

Benamar and researchers [97] have analysed the antifungal potential of extracts obtained from *Celtis australis*, *Chamaerops humilis*, *Asparagus albus*, and *Olea europea* var. *sylvestris* against blue mold disease caused by pathogen *Penicillium expansum* as well as gray mold disease caused by pathogen *Botrytis cinerea* in the postharvest apple fruit. Their findings revealed remarkable antifungal activity, particularly with the extract derived from *Celtis australis* and at 300 g/L concentration, which resulted in significant inhibition of mycelial growth (41% for *Botrytis cinerea* and 61% for *Penicillium expansum*), a notable reduction in incidence of diseases (43 and 48%), and a decrease in severity of diseases (39 and 50%), respectively. The phytochemical analysis revealed the presence of flavonoids and phenols in the tested extract samples.

80% aqueous extracts of *Eucalyptus globulus* on application to apples inoculated with *Colletotrichum gloeosporioides* and *Alternaria alternata* led to the lowest disease severity index of < 15% and lesion diameter of < 6.80 mm and the most favorable protective potentials of > 84.92% and inhibitory growth of > 85.45% [98]. Phytochemical analysis showed diverse common phenolic acids present in the plants under study namely: quinic acid, chlorogenic acid, caffeoylquinic acid, and gallic acid along with other flavonoids mainly catechin and quercetin. Xiao et al. [99] have isolated nine compounds from a medicine plant *Notopterygium incisum*, found only in China. These compounds include five linear furocoumarins (1 to 5), two phenylethyl esters (6 and 7), a faltarindiol (8), as well as one sesquiterpenoid (9). The study showed significant in vivo and in vitro antifungal activity against apple

pathogens of *Colletotrichum gloeosporioides* and *Botryosphaeria dothidea*. The study findings revealed that falcariindiol (8) possibly inhibited the germination of spores and new sporulation in *Botryosphaeria dothidea*, and also enhanced the membrane permeabilization in *Botryosphaeria dothidea* spores.

5.2 Mango

Worku and teammates [100] have combined the aqueous extracts from *Allium sativum* and *Ruta chalepensis* and gave hot water treatment (HWT) for evaluating their impact on management of mango postharvest anthracnose. The results revealed that the combination of treatments significantly ($p < 0.05$) affected the development of anthracnose on mangoes. The application of *Allium sativum* in combination with HWT at 55 and 50 °C, along with extract of *Ruta chalepensis* with HWT at same temperatures, was effective in reducing anthracnose intensity and improving marketability of mango fruit by over 80% with no effect on postharvest mango fruit quality indicators including weight loss, pH, TSS, TA.

5.3 Strawberries

Rashid and Aziz [101] have conducted a study on the aqueous extracts prepared from selected medicinal plants such as amethyst garlic, cloves, sumac, ginger, pelargonium, and cinnamon plants having the potential of inhibiting growth of newly isolated as well as identified *Botrytis cinerea* by well diffusion method for prevention of the postharvest losses encountered in strawberry fruits. The strawberry fruits were dipped in the extracts for 5 min to analyze their effects on pathogen protection and shelf life. Amethyst garlic and pelargonium manifested huge antifungal action against *B. cinerea* growth. The plant extracts considerably extended the fungal-inhibited strawberries' shelf life, maintained quality, and reduced their spoilage compared to control groups. Buzón-Durán et al. [102] have examined the bioactive components found in sea campion or *Silene uniflora* hydromethanolic extract, and the antimicrobial potential was evaluated both *ex situ* and in vitro against two phytopathogens infecting strawberry, namely *Colletotrichum nymphaeae* (causing anthracnose fruit rot) and *Botrytis cinerea* (causing grey mold). The main phytochemicals that were identified included mome inositol, cyclotetrasane, and saturated fatty acid esters. In vitro tests showed complete growth inhibition of *Colletotrichum nymphaeae* and *Botrytis cinerea* at 1500 and 1000 µg/mL extract concentrations, respectively. Ronga and co-workers [103] documented that the in vitro antifungal action of pomegranate peel aqueous extract (PAE) towards *Botrytis cinerea* is attributed to punicalagin prances that increase the strawberry shelf life. Using computational chemistry approaches, the authors showed that

amphotericin B (AmB) and punicalagin are characterized by similarity in molecular interaction properties, possibly connected to their capacity of forming pore-like aggregates.

5.4 Tomato

Extracts obtained from the leaves of *Vernonia amygdalina* and *Azadirachta indica* were applied on tomato fruits having inoculated with *Fusarium verticilloides* fungus at concentration of 10% w/v and the loss of weight (deterioration parameter) was examined over time [104]. The growth of fungal mycelia was significantly ($p < 0.05$) diminished by using plant extracts. In comparison with the control group, the plant extracts showed better results at 10% than the 5% w/v concentration. Mean weight loss in the treated fruits showed significant ($p < 0.05$) reduction throughout the experiment period compared to the control and untreated fruits. It was found that the neem leaf extract had more effectiveness. Palatability test carried out on the tomato fruits under treatment showed no significant variation in the fruit taste in the treated group and the untreated group, thus implying that both the plant extracts could be used for preserving tomato fruits in order to prolong their shelf life.

6 Challenges with plant extracts

The number of commercially available products derived from plant extracts as well as other natural compounds is very limited and hence, their share in global markets within crop protection products remains still negligible [105]. In 2020, the bio-fungicides market was valued at 1.6 billion USD, and is proposed to grow at 16.1% compound annual growth rate (CAGR) estimated to be 3.4 billion USD by 2025 [105]. On the contrary, the global market for fungicides is valued at 18.7 billion USD in 2019 with a projection of 24.5 billion USD by 2025 [105]. Nunes [106] have characterized the biocontrol agent development into two major stages: (1) the discovery phase, followed by (2) the commercial development phase. In the first phase, i.e., the discovery phase involves laboratory-based isolation, mode of action characterization as well as efficacy testing of the active compounds to production/process optimization and the pilot trials, along with patent applications for extracted active compounds or the microbes employed. Literature documents the success of first stage through scientific publications exceeding over 3000 in the year 2015 [107]. The second phase which includes commercial development comprises commercial scale trials involving scaling-up of production, toxicology assessments, final product formulation, along with product registration. The main challenges and constraints linked to commercialization of the plant extracts as well as other natural compounds get encountered in this phase and across the different steps

involved [105]. Ultimately, the high costs attributed to biocontrol production (involving formulation, commercial trials, along with toxicology screening), followed by registration and marketing still remain a limitation for commercial availability of these products. Likewise, the heavy regulatory barriers associated with registration in various countries remain an obstacle that discourages investors and hence, the commercialization phase [105]. A study by Bordoh et al. [108] has explained that the plant extract phytotoxicity could be attributed to some bioactive compounds found in the extracts with relatively higher concentrations, which interacted with the host cells and tissues, resulting in tissue damage and facilitating the fungi attack on the fruit and infestation.

7 Role of plant essential oils (EOs) in postharvest management of fungal pathogens of selected fruits

The essential oils are included amongst volatile organic compounds (VOCs), produced by microorganisms and plants as secondary metabolites [109]. They have been broadly studied as flavoring substances and aromas, appreciated for applications in food [109]. Moreover, they have received immense attention for the antimicrobial action they exert which is useful in postharvest processing [110, 111]. Since these are GRAS (Generally Recognized As Safe) substances, the same have been employed in the agro-food markets, and a few of them including thyme or *Thymus vulgaris*, mint oil or *Mentha rotundifolia*, and clove or *Syzygium aromaticum* has been considered into the pesticide database of the European Commission [110]. For the EOs action mechanisms as antimicrobial substances, it is essential to understand that their effectiveness depends not only on their chemical nature and concentration, but also on pathogen concentration and susceptibility, and even on the characteristics of the strain [109]. This capacity will differ depending on the nature and composition of the cell surface of microbes [109]. Furthermore, it is significant to understand and know the pathogenic mechanisms of action, depending on the fruit characteristics and environmental conditions [109].

Essential oils along with other lipophilic compounds tend to integrate into cell membrane and mitochondrial lipids, increasing membrane permeability and hence leading to cellular leakage [112, 113]. This further leads to lipid peroxidation followed by leakage of the cellular contents [114, 115]. Ergosterol is the key sterol present in fungal membranes which maintains cell function and integrity. Studies have indicated that higher bioactive agent concentrations like Eos cause disruption of ergosterol biosynthesis, thus reducing its membranal content [113]. Table 2 highlights various studies conducted to

explain the role of plant derived EOs in managing post-harvest fungal pathogens in selected fruits.

7.1 Apple

Francesco and researcher [124] have evaluated organic EOs obtained from *Thymus vulgaris*, *Rosmarinus officinalis*, and *Lavandula angustifolia* for their effects on apple pathogens in vivo and in vitro, in an integrated management form. In vitro results have revealed that *T. vulgaris* was the most active essential oil, both as biofumigant or agar infusion. In agar infusion, with lowest concentration starting from 0.2 mL/L, *Thymus vulgaris* reduced by 86.1%, 74.9%, 45.7%, and 66.9%, *Fusarium avenaceum*, *Botrytis cinerea*, *Neofabraea vagabunda*, and *Penicillium expansum* as well as mycelial growth, respectively. *Thymus vulgaris* as a biofumigant completely inhibited the mycelia pathogen growth in the tested samples. Xylia et al. [125] have investigated the effects of rosemary (Ros), eucalyptus (Euc) EO, their 50:50 v/v mixture and their common major component, eucalyptol, a monoterpenoid on the quality attributes, blue rot disease (caused by *Penicillium expansum*) inhibition, and fruit response in apple during the shelf life. This study revealed that growth of fungal colony decreased in vitro on exposure to rosemary EO at Ros-300 µL/L, eucalyptus EO at Euc-300 µL/L, and their mixture at Ros + Euc 300 and 100 µL/L. The exposure of Ros-100 µL/L aided in spore production stimulation, whilst eucalyptol at 100 µL/L and 300 µL/L and Euc + Ros at 100 µL/L and 300 µL/L caused a decrease in spore germination. Furthermore, the in vivo application of treatments led to decrease in *Penicillium expansum* lesion growth in apple fruits. EO present in *Melissa officinalis* is effective as antifungal agent against *Penicillium expansum*, *Rhizopus stolonifera*, and *Botrytis cinerea* [126]. The main components include p-menth-3-en-8-ol (8.8%), p-mentha-1,2,3-triol (13.1%), pulegone (8.8%), 2-piperitone oxide (7.3%), and piperitynone oxide (8.4%).

7.2 Mango

EOs of oregano, cinnamon bark, clove, and rosemary pepper inhibited 100% mycelial growth of *Alternaria alternata*, *Colletotrichum siamense*, *Botryosphaeria dothidea*, and *Lasiodiplodia theobromae* from mango having minimum inhibitory concentration (MIC) between 250 and 2000 µL/L [127]. The major compound found in pepper and rosemary oil was thymol (77.2%); in oregano it was carvacrol (69.1%); in cinnamon bark it was cinnamaldehyde (85.1%), and in cloves it was eugenol (84.84%). On evaluation of the antifungal potential of these compounds, carvacrol and thymol displayed greater inhibitory activity towards fungi. Six EOs viz., cinnamon, basil, peppermint, coriander, lemongrass, and orange for their chemical characteristics [128]. The antifungal action of essential oils was studied both in vivo and in vitro. The

Table 2 Effect of different plant essential oils (EOs) on postharvest fungi development on the four agricultural products

Essential oils plant	Application on fruit	Protection against type of pathogens	Outcome	References
<i>Thymus vulgaris</i> , <i>Satureja montana</i> , and <i>Ocimum basilicum</i>	Apple	<i>Botrytis cinerea</i>	Results indicated that savoury EO (1%) and thyme EO (1%) had equal effectiveness in hampering the grey mould rot disease development in vivo	[116]
<i>Pelargonium graveolens</i>	Apple	<i>Penicillium expansum</i> , <i>Rhizopus stolonifera</i> , and <i>Botrytis cinerea</i>	Investigations revealed that the <i>Pelargonium graveolens</i> -EO possessed dose-dependent effectiveness against the 3 tested phytopathogenic fungal strains	[117]
<i>Eucalyptus radiata</i> ssp. <i>radiata</i> , <i>Mentha pulegium</i> , <i>Rosmarinus officinalis</i> , <i>Origanum compactum</i> , <i>Lavandula angustifolia</i> , <i>Syzygium aromaticum</i> , <i>Thymus vulgaris</i> , <i>Citrus aurantium</i> , and <i>Citrus sinensis</i>	Apple	<i>Monilinia laxa</i> , and <i>Monilinia fructigena</i>	The tested higher concentrations of <i>Syzygium aromaticum</i> , <i>Citrus aurantium</i> , <i>Citrus sinensis</i> , and <i>Thymus vulgaris</i> EOs significantly decreased spore germination, lesion diameter, and brown rot incidence	[118]
<i>Cinnamomum zeylanicum</i> , and <i>Zingiber officinale</i>	Mango	<i>Colletotrichum gloeosporioides</i>	Disease severity and incidence were effectively controlled using 0.45% ginger EO and cinnamon EO at 0.075%	[119]
<i>Cymbopogon citratus</i> , <i>Rosmarinus officinalis</i> , <i>Cymbopogon winterianus</i> , <i>Melaleuca alternifolia</i> , and <i>Cinnamomum camphora</i> var. <i>linaloolifera</i>	Strawberries	<i>Botrytis cinerea</i> , and <i>Colletotrichum acutatum</i>	EOs tested in the study demonstrated fungicidal activity on both the phytopathogens, with concentrations varying between 0.05% to 0.20% v/v	[120]
<i>Mentha piperita</i> , <i>Satureja hortensi</i> , <i>Rosmarinus officinalis</i> , <i>Eucalyptus globulus</i> , <i>Citrus limon</i> , <i>Artemisia dracunculus</i> , and <i>Cuminum cyminum</i>	Strawberries	<i>Botrytis cinerea</i>	Peppermint and savory EOs were very effective against <i>Botrytis cinerea</i> growth at relatively lower concentrations owing to the dominant compound presence such as carvacrol (50.34%) and menthol (28.27%)	[121]
<i>Eucalyptus globulus</i> , and <i>Cymbopogon citratus</i>	Tomato	<i>Colletotrichum gloeosporioides</i>	Both EOs inhibited conidial germination and mycelial growth of the pathogen, however the one obtained from lemongrass displayed higher antifungal capacity	[122]
<i>Thamatococcus daniellii</i> , <i>Hyptis suaveolens</i> , and <i>Hildegardia barteri</i>	Tomato	<i>Aspergillus terreus</i> , <i>Fusarium oxysporum</i> , and <i>Geotrichum candidum</i>	In vitro bioassay indicated that the EOs were effective in inhibiting radial growth in the pathogenic fungi	[123]

results revealed that the pathogen isolated was *Colletotrichum acutatum*. Basil, lemongrass, and cinnamon EOs were effective in inhibiting the *Colletotrichum acutatum* growth in ascending order of lemongrass, basil, and cinnamon. The antifungal action was closely linked to the main components of EOs. The basil EOs were effective in controlling anthracnose disease development on the Cat Hoa Loc variety of mangoes artificially infected using *Colletotrichum acutatum*, and it was found to be effective as compared to the fungicide treatment.

7.3 Strawberries

Antifungal activities of *Ziziphora clinopodioides* and *Origanum onites* EOs against three diverse isolates (M2-1, M3-5, and M1-5) of *Botrytis cinerea* were examined (in in vitro testing) and investigations were conducted on the impact of the vapor contact on fungus as well as strawberry fruit quality (in in vivo testing) [129]. The results showcased that both *Ziziphora clinopodioides* and *Origanum onites* EOs exerted moderate to high effect on preventing the gray mold disease. Also, the oils were found to exert slight to moderate effect on the weight loss as well as soluble solids concentration loss. Strawberry

exposure to the EO vapors of *Thymus vulgaris* (Tv), *Origanum heracleoticum* (Oh), and *Cymbopogon citratus* (Cc) in commercial package decreased gray mold, with Oh and Tv exhibiting strong efficiency along with reduction in disease index by 57.69% and 53.85%, respectively. The Oh vapors in addition inhibited postharvest decay as well as maintained fruit quality, thus preventing soluble solid degradation and weight loss [130]. EOs of *Rosmarinus officinalis* and *Allium sativum* confirmed an expected potential fungicidal activity against *Colletotrichum nymphaeae* and also preserved the quality attributes in treated strawberries [131]. Decrease in fruit decay development as well as DS in fruits treated with of *Rosmarinus officinalis* and *Allium sativum* EOs might be linked to an increased phenolic content and defense-related enzyme activity such as peroxidase.

7.4 Tomato

The tomato gray mold disease caused by *Botrytis cinerea* is amongst the most devastating postharvest diseases. A study by Zhang et al. [132] explained the preparation of a thymol nano-emulsion (naming Nano-Thy) for the formation of a stable oil in water (O/W) microemulsion. The

researchers also found that the in vitro experiments on Nano-Thy displayed antifungal activity towards *Botrytis cinerea* by inhibition of mycelial growth as well as spore germination. The prepared Nano-Thy induced accumulation of ROS in mycelia, further causes lipid peroxidation, damage to cell membrane, and consequent cell death. Nano-Thy prevented the *Botrytis cinerea* infection on fresh tomatos significantly. Brito et al. [133] have explored the possibility of using EO mixtures and their individual hydrolates (HYSs) in controlling gray mold. Thus, HYSs and EOs were obtained from *Thymus vulgaris*, *Origanum vulgare*, *Citrus sinensis* and *Citrus limon* by hydrodistillation. Also, the in vitro antifungal potential was assessed and EC_{50} values of 15.9 $\mu\text{g/mL}$ for thyme and 19.8 $\mu\text{g/mL}$ for oregano EOs were obtained. These activities are attributed mainly to the volatile compounds, carvacrol and thymol. In vivo assay results showed that even though most of the tomatoes were infested after five days of inoculation, the damage was greatly reduced by an EO/HYS thyme mixture application. The indexes for tomato rot disease incidence caused by *Botrytis cinerea*, severity and % age of damaged fruits, measured after four days of inoculation, were diminished by 70 and 76%, respectively, as compared to the inoculum control. The results suggest that combination of EOs and HYSs enhanced antifungal activity, and the optimization of relative volumes, concentrations, along with the nature of compounds, might design a formulation capable of controlling *Botrytis cinerea* inoculum on the tomato fruits. EOs derived from *Zanthoxylum armatum* fruit when applied for managing *Alternaria alternata* rot disease at physiological levels showcased that EO could reduce *Alternaria* rot incidence in tomato considerably [134]. The gas chromatography-mass spectrometric profiling showed sabinene and eucalyptol as major components in EO derived from *Zanthoxylum armatum*. Furthermore, EO applied between 0.5 $\mu\text{L/mL}$ – 4.5 $\mu\text{L/mL}$ displayed significant growth inhibition in *Alternaria alternata* ($p > 0.05$) at tested concentration of 4.5 μL . Lipid peroxidation assays showed significant reduction in the membrane damage in tomatoes treated by EO in comparison to alone the fruits inoculated with *Alternaria alternata*. Increased activities of catalase, superoxide dismutase, glutathione reductase and ascorbate peroxidase, coupled with improved antioxidants such as glutathione, proline, total phenols, and ascorbic acid in fruits treated with EOs may be associated with enhanced fruit rot management as compared to the control fruits with *Alternaria alternata*-induced rot inoculation alone.

8 Challenges with EOs

Commercially, it has been documented that the main limitation related to the natural antimicrobials is their registration process. Several EOs components having

antimicrobial activity have been registered by United States as flavoring agents in different foods (carvone, carvacrol, cinnamaldehyde, p-cymene, eugenol, citral, limonene, thymol, and menthol), whilst others such as methyl eugenol and estragole are not allowed due to their genotoxicity [110]. At the same, there is a necessity to develop more toxicological studies comprehensively to assess the health risks associated with postharvest treatments and understand the mechanisms of decomposition for the aforementioned substances in organism in detail [110].

9 Role of edible films/coatings in postharvest management of fungal pathogens of selected fruits

Coatings /edible films have been defined as thinly layered (thickness < 0.3 mm) edible materials which tend to protect and enhance the quality of final product through regulation of oxygen, moisture, and solutes movement [135]. In spite of their similar functionality for the finished product, coatings and films have several different attributes [136]. Edible films constitute independent structures which are prepared by compression molding, extrusion, or solvent casting, and are used for wrapping the final product [106]. On the contrary, edible coatings are produced by food commodity dipping into the coating solution, or through spreading or spraying the coating solution onto the food surface [136]. Coatings/edible films can be made up of polysaccharides, lipids, proteins, and their combinations for obtaining composite materials with improved physicochemical properties in comparison to obtained packaging materials depending upon a single material [137]. Recently, active packaging containing plant extracts, natural biopolymers, probiotic microbes, and essential oils that are capable of effectively delaying the microbial spoilage and oxidation of food have been fabricated [138]. The major reasons for postharvest diseases in fruits are fungal and bacterial infections, along with damage. The strategy developed for covering fruits with edible coatings for prevention and reduction of postharvest diseases requires combination of active additives including natural extracts, antimicrobial chemicals, or biological inhibitors [139]. Table 3 highlights the role of different coatings/edible films to prevent postharvest fungal infections in several selected fruit crops.

9.1 Apple

The gel coatings made from antifungal *Aloe vera* (ALV) significantly decreased the severity of blue and gray mold diseases on inoculated apples, at a concentration of 150 $\mu\text{L/L}$ *Zataria multiflora* EO (ZMO)-based coating showcasing highest effectiveness. The ZMO + ALV coatings showed best results, displaying a low decay index, along with increased firmness, antioxidant activity, and total

Table 3 Effect of different edible films/coatings on postharvest fungi development on the four agricultural products

Nature of edible coatings/films	Enrichment of antimicrobials in edible coatings/films	Application on fruit	Protection against type of pathogens	Outcome	References
Chitosan	Extracts of chamomile, thyme, white rose, rose geranium, mentha, lavender, and cinnamon	Apple	<i>Penicillium expansum</i>	Results showed a 40% decay inhibition after seven days for chitosan	[140]
Chitosan	Cinnamon essential oil	Apple	<i>Penicillium expansum</i> , <i>Penicillium digitatum</i> , <i>Alternaria alternata</i> , and <i>Rhizopus stolonifer</i>	Study findings showed that the composite coating prepared from chitosan (CS) along with cinnamon essential oil (CEO) i.e., CS-CEO exhibited outstanding antifungal properties, with increment in the antifungal activity in correlation with CEO concentration	[141]
Pectin	Oregano essential oil	Mango	<i>Colletotrichum gloeosporioides</i>	Validation experiments carried out on the optimal coating in comparison to the untreated mango and commercial fungicide treated mangoes showed that the coating delayed ripening as well as effectively controlled the anthracnose incidence for 18 days with relative humidity of 85% and at 14 °C temperature	[142]
Chitosan	<i>Melaleuca alternifolia</i> essential oil	Mango	<i>Aspergillus</i> sp.	In vivo testing of the wounded mangoes showed a successful reduction in disease incidence	[143]
Alginate	<i>Lactocaseibacillus paracasei</i> , <i>Lactocaseibacillus rhamnosus</i> , and <i>Lactocaseibacillus plantarum</i>	Strawberries	<i>Rhizopus stolonifer</i>	Supplemented alginate coatings using probiotics showed a marked decrease in the pathogen colony counts, thus affirming their enhanced efficacy and safety	[144]
Chitosan	NA	Strawberries	<i>Botrytis cinerea</i>	Chitosan/glycerol 30% films (Chi/30%Gly) coated strawberries showed resistance against the attack of gray fungus along with an insignificant change in their flavor, aroma, texture, and appearance	[145]
Starch	Carvacrol	Tomato	<i>Alternaria alternata</i>	Edible coating derived from starch/gelatin and containing carvacrol was capable of inhibiting the <i>Alternaria alternata</i> growth at 0.3 mg carvacrol per gram of coating solution for the in vitro and in vivo antifungal assay	[146]

NA = not applicable

phenol content in the coated fruits [147]. Chitosan treatments combined with thyme EO when applied on apples (cv. 'Braeburn') exhibited inhibitory effects on *Botrytis cinerea* infection (– 48% of the infected wounds as compared to the untreated) [148]. Similarly, the clove EO in combination with chitosan decreased *Penicillium* infections in the 'Golden Delicious' apple cultivar by 62%. Hence, the results suggest effectiveness of the chitosan encapsulated EO use for controlling postharvest apple diseases during storage. The formulations of starch–gelatin (80:20) coating were applied to apple fruits to assess their effectiveness in controlling the respiration rate, weight loss, fungal decay, and fruit firmness during postharvest [149]. Thyme EO was incorporated at 0.25 g and 0.5 g/g of the polymer encapsulated or directly in lecithin to improve antifungal action. Coatings without lecithin decreased the severity and incidence of gray mold disease caused by *Botrytis cinerea* in apples despite the essential oil content.

9.2 Mango

A recent study analyzed the antifungal potential of edible coatings generated by incorporation of bioactive peptides produced by lacto-fermented palm kernel cake (PKC) already fermented with *Lactobacillus fermentum* ATCC9338 (PKCL2) and *Lactobacillus plantarum* (PKCL1) [150]. Incorporation of PKCL1 and PKCL2 with 10 diverse polysaccharide polymers, and evaluation of antifungal activity, peptide releasing ability, and biodegradability was carried out. The results revealed that the coating produced by incorporation of PKCL2 and PKCL1 in chitosan (CH) inhibited fungal growth commonly infesting mangoes. PKCL1 and PKCL2 containing CH coating displayed prominent inhibition zones towards *Botryodiplodia theobromae* and *Colletotrichum gloeosporioides*. Incorporating PKCL2 and PKCL1 CH matrix significantly ($p < 0.05$) decreased stem-end rot and anthracnose. The lactoperoxidase system (LPOS) is a natural antimicrobial system prevalent in human

secretions such as saliva, milk, and tears. It was incorporated into varying chitosan concentration solutions (0.5%, 1%, and 1.5%) for protecting mango fruits against two fungal strains viz., *Pestalotiopsis* sp. and *Phomopsis* sp. RP257 [151]. In vitro study on the chitosan concentration at a minimum of 1% containing or not, the lactoperoxidase system effectively inhibited 100% *Pestalotiopsis* species growth. Lactoperoxidase system (LPOS) or lactoperoxidase system along with iodine (LPOSI) presence in chitosan (0.5%) enhanced the inhibition %age from 26% to 93%. The edible films containing LPOS inhibited *Phomopsis* species RP257 specifically when LPOS was included in chitosan at 1% and 1.5% concentrations. Iodine did not have any impact on LPOS antifungal activity against *Pestalotiopsis* species but decreased the antifungal activity against *Phomopsis* sp. RP257. Recently, Ma et al. [152] have documented that the edible composite coating derived from shellac (a natural lipid polymer present in the insect secretions) as well as tannic acid (TA) aided in slowing down the respiration rate, delaying senescence and ripening, and postharvest prolonging the mango shelf life at room temperature. Excellent antifungal ability was displayed by TA-shellac coating against *Phomopsis mangiferae* and *Colletotrichum gloeosporioides*. Parente et al. [153] have fabricated an active chitosan-based coating with *Eucalyptus radiata* essential oil (EEO) and zinc oxide nanoparticles (ZnO-NPs) inhibiting decay and preserving postharvest mango quality. The developed coating attained 97.28% mycelial growth inhibition of *Lasiodiplodia theobromae* through in vitro plate assay. The study concluded that integration of the coating after sanitisation of mangoes and before packing them is favourable, and is also compatible with the cold-chain logistics operating at 9 °C.

9.3 Strawberries

The edible coatings derived from chitosan (CS) and carotenoproteins (CS-CP) have a beneficial effect on the strawberry quality under cold storage preservation [154]. In addition to the intrinsic antimicrobial and antioxidant activity, both CS and CS-CP edible coatings acted as a barrier towards pathogenic fungi present on the fruit surface. Another study utilized electrostatic spraying (ES) technique as an efficient and innovative technique for application of the edible alginate coating rich in methyl cinnamate and carvacrol (natural antimicrobial agents) on fresh strawberries [155]. The results have revealed that ES coating inhibited strawberry decay significantly with mere 5.6% infected fruits, in comparison to 16.6% for control and 8.3% for non-electrostatic spray (NES) fruits noticed after 13-day period of storage. After completion of 13-day storage period, the ES coating displayed superior performance on strawberry's firmness, weight loss reduction, and color retention.

9.4 Tomato

Thymus vulgaris EO and its coating based on carboxy methyl cellulose (CMC) were tested against most pathogenic fungus, *Fusarium cf. oxysporum* in tomatoes by Amoozegaran and co-workers [156]. The formulated coating containing 0.5% EO prevented fungal growth with 85.31% inhibition in inoculated tomato fruits after 9 days. With different storage periods of 11 days and 17 days, higher titratable acidity, lower mass loss, lower content of total soluble solids, and lower content of lycopene in coated fruits was observed as compared to uncoated ones. The study concluded that this coating could increase the fruit shelf life by forming a semi-permeable film on their surface.

10 Challenges with edible films/coatings

From the industrial perspective, one of the essential aspects in coatings/edible films is their storability [135]. This implies that the coating solution produced requires transformation into such a form that could maintain the active compounds' functionality and stability, while possessing easy transfer, use and storage. Freeze dried coating on mangoes effectively inhibited microbial growth and extended their shelf life by three days at temperature of 13 °C [157]. Extensive research is highly required owing to the data unavailability in this attractive area. The economics of innovative coatings/film techniques suggest their unprofitability at the industry scale, which is why fruit retailers and exporters rarely use these innovative methods, and stick to the traditional ones [135]. Still, it is expected that research be carried out for attaining an extended fresh fruit shelf life, without interfering with the nutritional and sensory properties, along with further research development at an initial stage and their use on a larger scale (industrial). The coatings and films which are prepared from natural edible materials have been found to be safe for humans use. But in case of nanomaterials, several factors have to be taken into consideration. Besides the benefits, it becomes equally important to understand and control the adverse effects and the impact they have on the ecosystem [158]. However, the current legislation remains concerned with nano technology and nanomaterials in general only, and not with the specific cases [159]. Additionally, the edible films generally have limited barrier and mechanical properties, thus limiting their utilization as real package. Hence, efforts are being made for management of these properties by utilizing multilayers or choosing nanotechnology as an alternative [160]. Another challenge is their hydrophilic nature, but the researchers have been working on it by adding such components in the films which are capable of competing in the current marketplace. In particular, the utilization of lipophilic compounds, including some essential oils (such as thyme, oregano,

and lemon essential oils) can be incorporated in protein- and polysaccharide-based films for improving moisture barrier, as reviewed previously [160].

11 Role of green metal nanoparticles (GMNPs) in postharvest management of fungal pathogens of selected fruits

At present, nanotechnology has proven that it has played a key role in agriculture science-related industries as well as pathogenic fields, predominantly in developing antifungal and antimicrobial agents [161]. A number of direct metal nanoparticles have been studied extensively, and these possess numerous biomedical applications. Alumina, iron oxide, titanium oxide, copper oxide, silver, selenium, calcium oxide, and zinc oxide are the methodologies developed by researchers and have demonstrated potential antimicrobial properties towards several microbes [162, 163]. Particularly, calcium oxide possessing high antimicrobial potential is employed not only as an acidity regulator in food additives but also serves as a preservative in food products [161]. However, consumption of direct metal nanoparticles has the identical side effects as with biological consumption. Therefore, researchers around the world are fabricating a new novel metal and plant fusion method in the field of nanotechnology. Phytochemically associated nanoparticles comprise of a potential novel, friendly, and simple model, and these are under focus of numerous scientists pertaining to their being the best mechanical way for application in agricultural and biological industries [164–166]. Plants and their components for phytochemical-derived nanoparticle production are of utmost importance in current drug as well as agent deployment fields owing to their low-cost production, non-toxic properties, and effective target regions [161]. The plant parts consist of extracts of minerals, vitamins, terpenoids, essential oils, and flavonoids. These organic ingredients provide an identical character for the nanoparticle production and improvement in their properties. Various plant parts are utilized for nanoparticle synthesis, such as leaves, stems, seeds, roots, flowers, and fruits [164–167]. The antifungal activity of GMNPs associated to elevated membrane leakages (proteins and sugars) in mycelial cell, lipid peroxidation, caused depression in respiratory chain dehydrogenase action and destroyed mycelia structure which led to phytopathogen death [168].

11.1 Apple

Calcium chloride nanoparticle (CRNPs) prepared from the extract of *Colchicum ritchii* flower have been studied for their action against apple pathogenic resistance and their property to extend shelf-life during storage [161]. The findings revealed that CRNPs possess excellent pathogenic resistance properties towards *Botryosphaeria*

dothidea while preserving taste by preventing metabolic changes and enhancing synthesis of sialic acid. Furthermore, shelf-life extension studies were conducted on fresh cut apples by their immersion in 40 µg/mL and 20 µg/mL CRNPs and a 2% standard solution of calcium chloride for five mins. The calcium chloride standard solution and the CRNPs proved to be good preservatives, and they preserved the apples with a shelf-life extending to 25 days. Fruit extract from *Pouteria caimito* derived calcium chloride (PCNP) in addition showed excellent inhibitory activity on the pathogenic infection in apples caused by *Botryosphaeria dothidea* [169]. Additionally, the PCNP proved that extension of apple slices shelf life to seven days. Green synthesized nanosilver (AgNPs) utilizing in vitro assay on black tea extract confirmed the antifungal activity of AgNPs towards *Monilinia fructigena* on application at 200 mg/L concentration and pre-incubated for four days, with 96.1% reduction in radial growth [170]. At the same dosage and preincubation period, the AgNPs resulted in a significant decrease in the fresh weight and diameter of brown rot lesions in apples artificially co-inoculated with *Monilinia fructigena* pathogen by 84.4% and 77.4%, respectively. Also, the AgNPs led to leakage of DNA and proteins from conidia of *Monilinia fructigena*.

11.2 Mango

Joshi et al. [171] have studied the antifungal potential of copper oxide nanoparticles (CuONPs) derived from *Azadirachta indica* against pathogen *Colletotrichum gloeosporioides*, responsible for anthracnose in mangoes. The in vitro studies showed a dose-dependent manner of fungal growth inhibition, attaining up to 77% inhibition at concentration of 1000 ppm. The post-harvest CuONPs application on mango cultivar Kesar at 200 ppm and 250 ppm concentrations achieved complete control of the disease. The results highlighted the possibility of green CuONPs for use as an effective and sustainable substitute to chemical fungicides, thereby addressing both food safety and plant health concerns. Additionally, to control disease, CuONPs improved the quality of post-harvest mango cultivar Kesar and extended their shelf life by delaying the ripening process.

11.3 Strawberries

AgNPs prepared from extract of *Euphorbia tirucalli* (aveloz, Av) through green synthesis showed good inhibitory action against *Botrytis cinerea* but had less effectiveness for *Rhizopus stolonifera* [172]. Antioxidant activity, total phenolic compounds, firmness, and fresh mass loss of strawberries had not been affected by Av-AgNPs. Strawberries under treatment had a respiratory rate lower than the control ones and displayed no symptoms

of microbial deterioration till 9-day period of storage, while it started on 3rd day in the control group.

11.4 Tomato

Albrahim et al. [173] have analysed the control of a fungal pathogen, *Alternaria alternata* accountable for the deterioration of tomatoes after harvest, using green-synthesized zinc oxide nanoparticles (ZnO-NPs) and copper oxide nanoparticles (CuO-NPs). Results showed that the 2 NPs showed significant dose-dependent antifungal action against *Alternaria alternata* with agar dilution method. At 2 mg/mL concentration, the ZnO-NPs and CuO-NPs induced a growth inhibition in fungi of about 1.85 ± 0.36 mm and 1.35 ± 0.45 mm respectively, in comparison to untreated control group (5.2 ± 0.23 mm). Interestingly, the combination of CuO-NPs and ZnO-NPs application resulted in significant reduction of the antifungal efficacy (3.11 ± 0.45 mm). Recently, Attique et al. [174] have demonstrated the application of *Terminalia chebula* fruit extract to prepare Iron oxide (Fe_2O_3) NPs along with their use in controlling the tomato fruit rot in Pakistan. The study led to formulation of an ecologically sound methodology to control the fruit rot disease in tomato caused by *Aspergillus fumigates* by exhibiting the highest efficacy and suppressing 88.54% mycelial growth in vitro. Fe_2O_3 NPs, with same concentration, markedly suppressed the tomato fruit rot progression (76%), in vivo. In another study, copper nanoparticles with 70 nm sizes were green synthesized using the *Rosmarinus officinalis* extract [175]. Results revealed that *Botrytis* growth was fully blocked in vitro, in case of copper nanoparticles addition at 15 mmol/L concentration to the fungal culture medium. Moreover, copper nanoparticles solution with concentration of 25 mmol/L were found to be most effective treatment towards fungal decay against artificially inoculated tomato fruits using *Botrytis cinerea*.

12 Challenges with GMNPs

Dikshit and co-workers [176] explained the many difficulties arise during GMNPs production, including extensive optimization experimentation on process parameters including temperature, rotation speeds, and pH values along with reactants such as quantity-types and plant materials-types of solvents, solvents' volumes, GMNPs appearing consistent in size and shape must be produced. In addition, with time, several reaction parameters require further optimization which is critical to maximize stability and yield of GMNPs thereby minimizing reaction time. A number of in vitro studies conducted have displayed the antimicrobial activity of nanoparticles synthesized from plant extracts. However, lack of in vivo data exerts considerable challenges for translation of these findings to practical applications.

13 Strength and limitations of the study

The current review successfully delivers postharvest management of pathogenic fungi causing infections on selected fruit crops through plant-based strategies and also throws lights on the challenges involved. Primarily, this review faces the challenge of lesser up-to-date literature availability related to the role of plant essential oils, extracts, edible coating/films along with green metallic nanoparticles for controlling postharvest fungal infections amongst the aforementioned crops. Additionally, majority studies describe the role of antifungal agents in postharvest fungal infections have been based on the in vitro data as well as in vivo studies derived on self-inoculation in place of the real time applications.

14 Conclusion

Plant extracts, plant-based essential oils, coatings/edible films as well as green metallic nanoparticles play a vital role in managing postharvest fungal infections in selected fruits. These natural fungicides effectively kill or inhibit postharvest fungi in addition to maintaining the overall fruit quality that is of utmost importance for retailers, farmers, and ultimate consumers. Nonetheless, upscaling at an industrial level and the commercialization of the plant-based fungicides remains a challenge for researchers. Even though there are challenges, yet some effective positive progress has taken place in this direction.

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