

Review Article

A REVIEW ON SUSTAINABLE ALTERNATIVES OF POST HARVEST TREATMENTS IN FRUITS

ABSTRACT

The fruit farming industry faces spoilage and disease after harvest, with *Colletotrichum* being the most common cause. Safer, more effective, biorational, and sustainable disease management are suggested. Plant-based essential oils (Eos) have synergistic antimicrobial, herbicide, insecticide, antioxidant, and fungicide properties that can fight agricultural fungi. Due to their negative effects on agroecosystems and public health, the OECD recommends a switch to sustainable food systems and synthetic fungicides. Essential oils are complex lipids from plants' secondary metabolism that are allelopathic, herbivorous, and phytopathogenic microorganism-protective. Their effects on bacteria and fungi include cell wall degradation, cytoplasmic and lipid membrane synthesis interference, lysis, cell death, and mitochondrial dysfunction. Essential oils **have been** **were** shown to treat postharvest diseases in apple cultivars and *Penicillium* spp., *B. cinerea* in strawberries and apples. Combining essential oils and non-toxic additives can control fruit postharvest fungal infections. Immersion, spraying, fumigation, and volatilization can apply them to fruit. Researchers suggest adding essential oils to edible/biodegradable films and coatings to extend fruit shelf life and reduce microorganism spoilage. Agriculture is promising with nanobiotechnologies that improve volatile compound stability, pesticide residual effects and *Aedes aegypti* adhesion and repellency. Further research is needed to determine nanomaterials' toxicity and environmental impact.

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Keywords: *Colletotrichum*, fungicides, essential oils, agroecosystems, nanobiotechnologies.

1. INTRODUCTION:

Fruit farming is booming because it provides nutrients, antioxidants, vitamins, and fibers [1]. After harvest, spoilage and disease destroy over half of fruit production [2]. Fungi-caused spoilage reduces food's shelf life, antioxidant and vitamin levels, health benefits, and waste, depleting natural resources [21]. The most common cause of postharvest diseases is fungi, and ***Colletotrichum*** can infect almost any fruit tree [3]. These fungi's latent or dormant pre-harvest infections can threaten fruit quantity and marketability. Synthetic fungicides have been used to prevent fruit deterioration after harvest. However, excessive synthetic fungicide use may harm the environment, human health, and economy [4, 5, 6, 7, 8]. The demand for pesticide-free food has led to safer, more effective, biorational, and sustainable disease management [10,11]. Essential oils from plants are a promising new tool for fighting agricultural fungi. These complex lipids contain bioactive compounds with synergistic antimicrobial, herbicide, insecticide, antioxidant, and fungicide properties [9, 36, 13, 14, 15, 16]. This review discusses the main aspects of obtaining, using, forms of application, particularities, and antimicrobial effectiveness of EO composites in food powder preservation postharvest, highlighting their mechanisms of action. This study will help provide nutritious food to the world by preventing postharvest fungal disease in fruits.

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2. Population growth and food security

To ensure global food security, production losses and postharvest damage must be reduced by 2050 as the world's population reaches 9 billion [17, 10, 19, 20]. Around 30% of food is wasted, lost, spoiled, or damaged by pests and diseases, costing billions. This could feed 820 million daily and 2 billion by 2050. Postharvest losses in developing countries can exceed 50% of productivity [21, 23, 24]. Latent infections and injuries during harvest, post-harvest, and fruit transport make post-harvest quality management difficult in fruit growing. These losses reduce product shelf life, nutritional value, and food safety [7]. The OECD recommends improving environmental resource efficiency and agriculture resilience to transition to more sustainable food systems [10, 19]. Synthetic fungicides harm agroecosystems and create pathogens resistant to active ingredients, raising concerns about their use in agriculture. Public health concerns about fungicide residues also concern consumers [25]. Food health and environmental concerns from government and society are affecting production. The UN declared 2020 the International Year of Plant Health to promote food security, environmental protection, and phytosanitary and regulatory policies. Alternative phytosanitary control technologies must prevent food loss, ensure nutritional integrity, meet market demands, and save energy [26, 5, 27, 28, 18].

3. The genus *Colletotrichum* and infection strategy

Postharvest diseases are caused by fungi, including *Colletotrichum*, an Ascomycota and Sordariomycetes. A globally distributed genus, *Colletotrichum* causes economically significant losses of temperate, subtropical, and tropical fruits [30, 31, 32, 19, 33, 34]. The wide diversity of hosts, phenotypic and genotypic heterogeneity, and potential for cross-inoculation make it vulnerable and economically important. *Colletotrichum* species can infect several host species, making it the eighth genus causing economically important fruit and vegetable diseases [35,36]. *Colletotrichum* spreads through airborne conidiospores on healthy commercial fruits and vegetable fragments [3, 37]. In favorable conditions, conidiospores germinate and form infectious structures that can penetrate plant cell cuticles [38]. Germinal tubes, appressorium, haustoria, secondary necrotrophic intracellular hyphae, and acervuli [29, 3, 4, 6, 8]. The infection process involves *Colletotrichum* spp. adhere to the host surface through hemicellulose mucilage, where needle-shaped penetrating hypha pierce the cuticle and epidermal cell wall to colonize the tissue. Cuticle penetration or entry through stomata, lenticels, wounds, or scar tissue abscesses can cause infection [37]. Most emerging colonies interact biotrophically with infected tissues and remain inactive for short or long periods [39]. The fruit's pre-climatic stage, when anthracnose develops, is the most critical stage. Lesions merge and rot, reaching part of the fruit or causing necrosis under favorable conditions [40, 41]. Under poor growing conditions, *Colletotrichum* spp. sclerotia in vegetative or reproductive remains or soil for infection [12]. Fruit farming is affected by anthracnose because it can cause significant economic losses [29].

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4. Postharvest management

In exporting countries, accidental fungal infections can reduce fresh fruit supply, farmers' incomes, market value, nutritional quality, and profitability [34]. Climacteric fruits like banana, guava, avocado, pear, mango, and papaya are perishable and susceptible to infections, so they must be prevented [42]. These fruits are treated with synthetic fungicides and heat. Hydrothermal treatment is safe and non-polluting, but improper use can compromise fresh product nutritional quality and taste [43, 9]. Synthetic chemical fungicides are the most common treatment for *Colletotrichum* spp. They can kill, repel, or reduce any pathogenic organism that threatens production [45, 36]. The indiscriminate use and ineffective application techniques have compromised their efficiency and sustainable production. Epidemiological studies and sustainable short-term use of pesticides with the same systemic active principle and applications that differ from package inserts have led to control failures, favoring the emergence of resistant phytopathogens and low sensitivity to market-available active principles [3, 26, 46, 47, 8]. The social-economic impact of excessive agrochemical use in agriculture is significant because non-target organisms may be toxic or genotoxic, threatening survival, fertility, and genetic composition. Natural ecosystems and crop safety depend on pollinator decline. Essential oils are popular due to their compound diversity and synergistic action [26, 45, 50, 47].

4.1 Essential oils in plant protection

Essential oils (Eos) are complex lipids from plants' secondary metabolism that are lipid-soluble and organic solvent-soluble. Volatile compounds that are not essential for plant survival perform allelopathic, herbivorous, phytopathogenic microorganism protection, and attract disseminators and pollinators [51]. Multiple chemotypic variations make EOs appealing to pharmaceutical, food, chemical, and agronomic industries [52, 78, 11, 54]. Terpenoids (monoterpenes and sesquiterpenes) and phenylpropanoids are the two main chemical groups of EOs. Terpenes dominate, acting alone or together. The concentration and yield of these compounds vary by species, season, harvest location, soil and climatic conditions, photoperiod, genetic factors, and pre-drying and extraction technology [55, 51, 56]. EOs seem to work similarly in bacteria and fungi, but mechanisms are unknown. The effects involve cell wall degradation, interference in cytoplasmic and lipid membrane synthesis, lysis, and cell death. EOs can disrupt mitochondrial respiratory chain complexes, oxidative phosphorylation, and mitochondrial dysfunction, causing metabolic imbalance [39].

Botrytis cinerea exposed to lemongrass essential oil showed vesiculation, cytoplasmic rupture, and collapsed hyphae in light and scanning electron microscopy [55, 51, 56, 54]. Antifungals deactivate fungi by disrupting cell membranes or organelles or inhibiting nuclear material or protein synthesis [56, 57]. Turmeric essential oil disrupts plasma membrane integrity and mitochondrial dysfunction, stagnating fungi metabolism. Melaleuca alternifolia EO reduced *Botrytis cinerea*'s mitochondrial and tricarboxylic acid cycle enzymatic activities, causing energy loss [57]. The action mechanism of chemical compounds in essential oils [EOs] is interesting

because they can act together [59, 38, 56]. Oregano and thyme EOs have synergistic effects against *Aspergillus parasiticus*, *Penicillium chrysogenum*, and peppermint-tea tree. Inhibiting phytopathogenic fungi with EOs and compounds is recommended. Complex, natural, biodegradable EOs have low toxicity to non-target organisms and high toxicity to pathogens, yielding satisfactory results with low resistance [52]. EOs' complexity makes them a fungicide-reduction alternative in agriculture. Due to their volatility and low solubility, more research is needed to understand their manipulation, dosage, and target organism effect. EOs can maintain plant integrity and control or prevent fruit tree pests and diseases, especially for export and organic agriculture without synthetic compounds [60, 61, 58, 62, 63, 64]. Essential oils are extracted using steam distillation, organic solvent extraction, supercritical CO₂, cold pressing, and hydro distillation [95]. Hydro distillation is the most cost-effective way to extract plant EO. In vitro and in vivo experiments screen compounds' fungicidal and fungistatic effects for commercial viability [4, 65]. Nanotechnologies like edible coating, encapsulation, and stable microemulsions can be used to incorporate active compounds in EOs to inhibit or eliminate spoilage fungi [66, 67, 68].

4.1.2 *Colletotrichum* spp.

Lemongrass, cloves, basil, cinnamon, melaleuca, mint, ginger, and rosemary are *Colletotrichum*-fungicidal. These essential oils have antifungal properties and can prevent anthracnose, deterioration, and fruit quality without affecting ripening. EOs inhibit fungal activity depending on concentration and species [69]. Satureja, thyme, Melissa officinalis, and oregano EOs have been shown to treat postharvest diseases in apple cultivars. The EOs have also been reported for postharvest pathogens like *B. cinerea* in apple fruit, *P. digitatum*, *B. cinerea* and *Rhizopus stolonifer* in strawberries, basil and rosemary EOs on bananas with anthracnose, Alfavaca, fennel, lipia, and *Baccharis trimera* [70]. *Baccharis dracunculifolia* EO showed fungistatic action, while *Baccharis trimera* EO completely inhibited *Colletotrichum acutatum* conidium germination [71]. The F-EO. vulgar and *B. trimera* prevented and treated grape rots. Some oils can inhibit fungal growth better than commercial fungicides but are not 100% effective on pathogens. EOs inhibit fungal growth better than other postharvest pathogens like *Penicillium* spp., *B. cinerea* in Apples and strawberries [72–77]. However, many obstacles remain to fully utilize essential oils as biopesticides. The compounds' volatile, photodegradable, thermolabile, oxidative, and low water solubility limit their use in fruits. The reproducibility of materials is also affected by the difficulty of registering diverse mechanisms of action and molecular targets [78, 54].

4.1.3 Methods of applications

Essential oils (Eos) and non-toxic additives can control fruit postharvest fungal infections. Studies have shown that inhibiting or eliminating spoilage fungi improves EO effectiveness [54]. Immersion or spraying EOs on fruit has worked for many species [4, 65]. Fumigation and volatilization diffuse allelochemical compounds into the air, affecting nearby organisms. Food treated with EOs in packaging or modified atmosphere reduces anthracnose in avocado, papaya, mango, and straw berries [95]. Researchers suggest combining various methods, such as adding essential oils to edible/biodegradable films and coatings, to extend fruit shelf life. These technologies extend shelf life and reduce microorganism-induced spoilage in fruit storage and retail [79]. However, more research is needed to apply EOs to food and promote sustainable agriculture.

EO bioactivities are being optimized or enhanced using micro- and nanotechnologies. Nanotechnologies can overcome preservation technology flaws and transport bioactive molecules to extend fruit shelf life. Edible coating, encapsulation, and stable microemulsions improve essential oil stability [66, 67, 68].

4.1.4 Biodegradable paints

Fresh fruit quality and shelf life are being preserved with edible films and coatings. These hydrophobic coatings increase fruit antifungal properties and reduce biochemical ripening deterioration [80, 81]. The fruit's semi-permeable film acts as an isolation membrane, slowing cellular oxidative activities and preventing water, gases, oils, and pathogens from entering [82, 83, 84]. This membrane also protects the fruit from external contaminants and infections, reducing the risk of fungal lesions [85, 86]. Edible films and coatings use tasteless, transparent, animal or vegetable-based raw materials that do not impair food sensory properties [11]. Filmogens can carry active ingredients, improving compound emulsion, stability, and kinetics. Active packaging uses essential oils as additives to provide nutritional and antifungal benefits [54]. Several studies have shown that postharvest coating and EO can protect fruits from phytopathogenic attack, control natural deterioration, and preserve quality in an economically and environmentally friendly way [87, 9]. Their responses vary by fruit and coating, which is their

main drawback. The antifungal properties of filmogens and EOs are thought to work together. The feasibility of their large-scale use in product conservation and the environmental impacts of these coatings' raw materials make continuous studies valuable [76].

5. Nanobiotechnology

Agriculture is promising for nanobiotechnologies, which aim to create polymer or copolymer matrix with nanoscale particulates. Slow release of essential oils (Eos) into the environment using nano emulsion, biopolymers, nanoparticles, or encapsulation improves stability and bioavailability [88, 89, 90, 91]. This technology isolates specific, sustainable, and safe bioactive compounds for the food industry, reducing pesticide residues [28, 90]. Nano emulsions improve solubility, cell membrane permeation, and volatile compound stability [82]. They also improve *Aedes aegypti* adhesion and repellency and anise essential oil stability against stored grain pests. Encapsulation technology controls bioactive molecule release, reducing particle size and improving bioactive compound durability [66, 92, 93]. Nanobiotechnologies can prevent premature degradation in harsh environmental conditions, making them promising for sustainable agriculture. However, nanomaterials' long-term toxicity and environmental effects must be considered. More productive agriculture and less harm to non-target organisms require more research on fate, effects on pathogens, humans and the environment, and customization [94].

6. Conclusions

This review highlights the growing environmental and social impacts of fungicide use in agroecosystems. Resistance from selective pressure makes conventional agriculture unsustainable and unable to meet population food needs. New active ingredients, methods, and disease management strategies are needed to fight fungal diseases. An ecological and sustainable phytosanitary control alternative for *Colletotrichum* postharvest diseases is essential oils (Eos). EOs preserve plant tissue and may be a promising alternative for controlling or reducing diseases in fruit trees, especially export trees. The chemical composition and bioactive compounds of EOs determine their postharvest disease control. New fungicides that meet consumer needs and promote the circular economy are promising for agriculture. Sustainable food applications, disease control, and food safety can use EOs. More research is needed to determine their side effects and safety. Essential oils are a promising synthetic pesticide alternative, improving global food security.

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