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A Review on Sustainable Alternatives of Post Harvest Treatments in Fruits

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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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 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 be applied to fruit. Researchers suggest adding essential oils to edible or 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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1. INTRODUCTION

Fruit farming is booming because it provides nutrients, antioxidants, vitamins, and fiber [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 talks about how to get EO composites, how to use them, how to apply them, what makes them different, and how well they work as antimicrobials in food powder preservation after harvest. It also talks about how they work. This study will help provide nutritious food to the world by preventing postharvest fungal disease in fruits.

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]. Pests and diseases waste, spoil, lose, or damage about 30% of the food supply, which costs billions. This could feed 820 million people 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 the 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*, 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 fruit 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. adhering 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 of time [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 can cause infection

[12]. Fruit farming is affected by anthracnose because it can cause significant economic losses [29].

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 and 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 effects. 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 add active compounds to EOs to stop or get rid of spoilage fungi [66, 67, 68].

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 utilizing essential oils as biopesticides. The compounds' volatile, photodegradable, thermolabile, oxidative, and low water solubility limit their use in fruits. The difficulty of registering various mechanisms of action and molecular targets also affects the reproducibility of materials [78, 54].

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 a modified atmosphere reduces anthracnose in avocado, papaya, mango, and straw berries [95]. Researchers suggest combining various methods, such as adding essential oils to edible or 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].

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 matrixes with nanoscale particulates. Slow release of essential oils (Eos) into the environment using nanoemulsions, biopolymers, nanoparticles, or encapsulation improves stability and bioavailability [88, 89, 9, 90, 91]. This technology isolates specific, sustainable, and safe bioactive compounds for the food industry, reducing pesticide residues [28, 90]. Nanoemulsions 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 by 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 to selective pressure makes conventional agriculture unsustainable and unable to meet the population's food needs. New active ingredients, methods, and disease management strategies are needed to fight fungi. 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.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Mason-D'Croz D, Bogard JR, Sulser TB, Cenacchi N, Dunston S, Herrero M et al. Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. Lancet Planet Health. 2019;3(7):e318-29.
2. Ncama K, Mditshwa A, Tesfay SZ, Mbili NC, Magwaza LS. Topical procedures adopted in testing and application of plant-based extracts as bio-fungicides in controlling postharvest decay of fresh produce. Crop Prot. 2019;115:142-51.
3. Cannon PF, Damm U, Johnston PR, Weir BS. *Colletotrichum* – current status and future directions. Stud Mycol. 2012;73(1): 181-213.
4. Ali A, Bordoh PK, Singh A, Siddiqui Y, Droby S. Post-harvest development of anthracnose in pepper (*Capsicum spp*): etiology and management strategies. Crop Prot. 2016;90:132-41.
5. Mari M, Bautista-Baños S, Sivakumar D. Decay control in the postharvest system: role of microbial and plant volatile organic compounds. Postharvest Biol Technol. 2016;122:70-81.
6. Munir M, Amsden B, Dixon E, Vaillancourt L, Gauthier NAW. Characterization of *Colletotrichum* species causing bitter rot of apple in Kentucky orchards. Plant Dis. 2016;100(11):2194-203.
7. González-Estrada RR, Chalier P, Ragazzo-Sánchez JA, Konuk D, Calderón-Santoyo M. Antimicrobial soy protein-based coatings: application to Persian lime (Citrus latifolia Tanaka) for protection and preservation. Postharvest Biol Technol. 2017;132:138-44.
8. Zhang L, Song L, Xu X, Zou X, Duan K, Gao Q. Characterization and Fungicide Sensitivity of *Colletotrichum* Species Causing Strawberry Anthracnose in Eastern China. Plant Disease. 2020;10:19-2241.
9. Zhang X, Guo Y, Guo L, Jiang H, Ji Q. *In vitro* evaluation of antioxidant and antimicrobial activities of Melaleuca alternifolia essential oil. BioMed Research International. 2018;1–8.
10. OECD/FAO. Background Notes on Sustainable, Productive and Resilient Agro-Food Systems: Value chains, human capital, and the 2030 Agenda. In Background Notes on Sustainable, Productive and Resilient Agro-Food Systems; 2019a.
11. Marangoni Júnior L, Cristianini M, Anjos CAR. Packaging aspects for processing and quality of foods treated by pulsed light. J Food Process Preserv. 2020;44(11).
12. Bazie S, Ayalew A, Woldetsadik K. Integrated management of postharvest banana anthracnose (*Colletotrichum musae*) through plant extracts and hot water treatment. Crop Protection. 2014;66:14–18.
13. Jahani M, Pira M, Aminifard MH. Antifungal effects of essential oils against Aspergillus niger in vitro and in vivo on pomegranate (*Punica granatum*) fruits. Sci Hortic. 2020;264:109188.

14. Matos LF, Barbosa DReS, Lima E. da C, Dutra K. de A., Navarro, D. M. do AF, Alves JLR, Silva, G. N. Chemical composition and insecticidal effect of essential oils from Illicium verum and *Eugenia caryophyllus* on Callosobruchus maculatus in cowpea. Industrial Crops and Products. 2020;145:112088.
15. Mehdizadeh L, Taheri P, Ghasemi Pirbalouti A, Moghaddam M. Phytotoxicity and antifungal properties of the essential oil from the *Juniperus polycarpos* var. turcomanica (B. Fedsch.) R.P. Adams leaves. Physiol Mol Biol Plants. 2020; 26(4):759-71.
16. Raspo MA, Vignola MB, Andreatta AE, Juliani HR. Antioxidant and antimicrobial activities of citrus essential oils from Argentina and the United States. Food Biosci. 2020;36:100651.
17. Crous PW, Groenewald JZ, Slippers B, Wingfield MJ. Global food and fibre security threatened by current inefficiencies in fungal identification. Philos Trans R Soc Lond B Biol Sci. 2016;371(1709):20160024.
18. OECD. FAO agricultural outlook 2019-2028. OECD.
19. Porat R, Lichter A, Terry LA, Harker R, Buzby J. Postharvest losses of fruit and vegetables during retail and in consumers' homes: quantifications, causes, and means of prevention. Postharvest Biol Technol. 2018;139:135-49.
20. Spagnol WA, Silveira Junior V, Pereira E, Guimarães Filho N. Redução de perdas nas cadeias de frutas e hortaliças pela análise da vida útil dinâmica. Braz J Food Technol. 2018;21:Article e2016070.
21. Henz GP. Postharvest losses of perishables in Brazil: what do we know so far? Hortic Bras. 2017;35(1):6-13.
22. Mathabe PMK, Belay ZA, Ndlovu T, Caleb OJ. Progress in proteomic profiling of horticultural commodities during postharvest handling and storage: a review. Sci Hortic. 2020;261:108996.
23. Ahmad MS, Siddiqui MW. Factors affecting postharvest quality of fresh fruits. Postharvest Qual Assur Fruits Pract Approaches Dev Ctries. 2015:(7-32).
24. FAO, Food and Agriculture Organization of the United Nations - FAO (). El estado mundial de la agricultura y la alimentación. Progresos en la lucha contra la pérdida y el desperdicio de alimentos. In Idesia. 2019;32:3.
25. Yan D, Zhang Y, Liu L, Yan H. Pesticide exposure and risk of Alzheimer's disease: A systematic review and meta-analysis. Scientific Reports. 2016;6:1–9.
26. Lamichhane JR, Dachbrodt-Saaydeh S, Kudsk P, Messéan A. Conventional pesticides in agriculture: benefits *versus* risks. Plant Dis. 2016;100(1):10-24.
27. Usall J, Ippolito A, Sisquella M, Neri F. Physical treatments to control postharvest diseases of fresh fruits and vegetables. Postharvest Biol Technol. 2016;122:30-40.
28. Chowdhary K, Kumar A, Sharma S, Pathak R, Jangir M. *Ocimum sp.*: source of biorational pesticides. Ind Crops Prod. 2018;122:686-701.
29. Bailey JA, Jeger M. Colletotrichum: Biology, Pathology and Control. 1992 (CABI; Inte).
30. Damm U, Cannon PF, Woudenberg JHC, Crous PW. The *Colletotrichum acutatum* species complex. Stud Mycol. 2012;73(1) :37-113.
31. Berry EM, Dernini S, Burlingame B, Meybeck A, Conforti P. Food security and sustainability: can one exist without the other? Public Health Nutr. 2015;18(13):2293-302.
32. El Ouadi Y, Manssouri M, Bouyanzer A, Majidi L, Bendaif H, Elmsellem H et al. Essential oil composition and antifungal activity of Melissa officinalis originating from north-Est Morocco, against postharvest phytopathogenic fungi in apples. Microb Pathog. 2017;107:321-6.
33. Gerum ADA, Santos GS, Santana MDA, Souza JDS, Cardoso CEL. Fruticultura tropical: potenciais riscos e seus impactos. In: *EMBRAPA* – Embrapa Mandioca e fruticultura – documentos; 2019 (INFOTECA-E).
34. Md Nor S, Ding P. Trends and advances in edible biopolymer coating for tropical fruit: a review. Food Res Int. 2020;134:109208.
35. Dean R, Van Kan JAL, Pretorius ZA, Hammond-Kosack KE, Di Pietro A, Spanu PD et al. The Top 10 fungal pathogens in molecular plant pathology. Mol Plant Pathol. 2012;13(4):414-30.
36. Feng G, Zhang XS, Zhang ZK, Ye HC, Liu YQ, Yang GZ, Zhang J. Fungicidal activities of camptothecin semisynthetic derivatives against Colletotrichum gloeosporioides in vitro and in mango fruit. Postharvest Biology and Technology. 2019;147:139–147.

37. Singh D, Sharma RR. Postharvest Disinfection of Fruits and Vegetables. 2018;1–52.
38. Nazzaro F, Fratianni F, Coppola R, De Feo V. Essential oils and antifungal activity. Pharmaceuticals (Basel). 2017;10(4):1-20.
39. O'Connell RJ, Thon MR, Hacquard S, Amyotte SG, Kleemann J, Torres MF et al. Lifestyle transitions in plant pathogenic Colletotrichum fungi deciphered by genome and transcriptome analyses. Nat Genet. 2012;44(9):1060-5.
40. Saxena A, Raghuwanshi R, Gupta VK, Singh HB. Chilli anthracnose: The epidemiology and management. Frontiers in Microbiology, 2016;7:1–18.
41. Fischer IH, de Moraes MF, Firmino AC, Amorim L. Detection and epidemiological progress of quiescent avocado diseases. Cien Rural. 2019;49(8):1-10.
42. Botelho LNS, Rocha DA, Braga MA, Silva A, de Abreu CMP. Quality of guava cv. 'Pedro Sato' treated with cassava starch and cinnamon essential oil. Sci Hortic. 2016;209:214-20.
43. Maringgal B, Hashim N, Tawakkal ISMA, Mohamed MTM, Hamzah MH, Shukor NIA. The causal agent of anthracnose in papaya fruit and control by three different Malaysian stingless bee honeys, and the chemical profile. Sci Hortic. 2019;257:108590.
44. Zhang M, Liu W, Li C, Shao T, Jiang X, Zhao H, & Ai. Postharvest hot water dipping and hot water forced convection treatments alleviate chilling injury for zucchini fruit during cold storage. Sci Hortic. 2019;249:219-27.
45. Songa EA, Okonkwo JO. Recent approaches to improving selectivity and sensitivity of enzyme-based biosensors for organophosphorus pesticides: *a review*. Talanta. 2016;155:289-304.
46. He J, Wu D, Zhang Q, Chen H, Li H, Han Q, Qin W. Efficacy and mechanism of cinnamon essential oil on inhibition of Colletotrichum acutatum isolated from "Hongyang" kiwifruit. Frontiers in Microbiology. 2018;9:1–12.
47. Chechi A, Stahlecker J, Dowling ME, Schnabel G. Diversity in species composition and fungicide resistance profiles in Colletotrichum isolates from apples. Pestic Biochem Physiol. 2019;158:18-24.
48. Bragança CAD, Damm U, Baroncelli R, Massola Júnior NS, Crous PW. Species of the Colletotrichum acutatum complex associated with anthracnose diseases of fruit in Brazil. Fungal Biol. 2016;120(4):547-61.
49. Chen SN, Luo CX, Hu MJ, Schnabel G. Sensitivity of *Colletotrichum* species, including *C*. fioriniae and C. nymphaeae, from Peach to Demethylation Inhibitor Fungicides. Plant Dis. 2016;100(12):2434-41.
50. Hawkins NJ, Bass C, Dixon A, Neve P. The evolutionary origins of pesticide resistance. Biol Rev Camb Philos Soc. 2019;94(1):135-55.
51. Gutiérrez-del-Río I, Fernández J, Lombó F. Plant nutraceuticals as antimicrobial agents in food preservation: terpenoids, polyphenols and thiols. Int J Antimicrob Agents. 2018;52(3):309-15.
52. Oliveira J, Gloria EM, Parisi MCM, Baggio JS, Silva PPM, Ambrosio CMS et al. Antifungal activity of essential oils associated with carboxymethylcellulose against *Colletotrichum acutatum* in strawberries. Sci Hortic. 2019;243:261-7.
53. Marangoni Júnior L, Vieira RP, Jamróz E, Anjos CAR. Furcellaran: an innovative biopolymer in the production of films and coatings. Carbohydr Polym. 2021;252:117221..
54. Vianna TC, Marinho CO, Marangoni Júnior LM, Ibrahim SA, Vieira RP. Essential oils as additives in active starch-based food packaging films: a review. Int J Biol Macromol. 2021;182(1):1803-19..
55. Freiesleben S, Jager AK. Correlation between plant secondary metabolites and their antifungal mechanisms–A review. Med Aromat Plants. 2014;3(2):1-6.
56. Tariq S, Wani S, Rasool W, Shafi K, Bhat MA, Prabhakar A et al. A comprehensive review of the antibacterial, antifungal and antiviral potential of essential oils and their chemical constituents against drug-resistant microbial pathogens. Microb Pathog. 2019;134:103580.
57. Raveau R, Fontaine J, Lounès-Hadj Sahraoui A. Essential oils as potential alternative biocontrol products against plant pathogens and weeds: a review. Foods. 2020;9(3):31.
58. Li Y, Shao X, Xu J, Wei Y, Xu F, Wang H. Tea tree oil exhibits antifungal activity against Botrytis cinerea by affecting mitochondria. Food Chem. 2017;234:62-7.
59. Hu Y, Zhang J, Kong W, Zhao G, Yang M. Mechanisms of antifungal and anti-

aflatoxigenic properties of essential oil derived from turmeric (*Curcuma longa* L.) on *Aspergillus flavus*. Food Chem. 2017;220:1-8.

60. Yu D, Wang J, Shao X, Xu F, Wang H. Antifungal modes of action of tea tree oil and its two characteristic components against *Botrytis cinerea*. J Appl Microbiol. 2015;119(5):1253-62.
61. Sogvar OB, Koushesh Saba M, Emamifar A. Aloe vera and ascorbic acid coatings maintain postharvest quality and reduce microbial load of strawberry fruit. Postharvest Biol Technol. 2016;114:29-35.
62. Chávez-Magdaleno ME, González-Estrada RR, Ramos-Guerrero A, Plascencia-Jatomea M, Gutiérrez-Martínez P. Effect of pepper tree (*Schinus molle*) essential oil-loaded chitosan bio-nanocomposites on postharvest control of Colletotrichum gloeosporioides and quality evaluations in avocado (*Persea americana*) cv. Hass. Food Sci Biotechnol. 2018;27(6):1871-5.
63. Betchem G, Johnson NAN, Wang Y. The application of chitosan in the control of postharvest diseases: a review. J Plant Dis Prot. 2019;126(6):495-507.
64. Madjouko MA, Tchameni SN, Tchinda ES, Dongmo Jazet PM, Kamsu PN, Medzue Souop Kamga VA et al. Inhibitory effects of essential oils from *Ocimum basilicum* and *Ocimum gratissimum* on *Colletotrichum musae*: the causal agent of bananas anthracnose. J Phytopathol. 2019;167(5):257-64. doi: 10.1111/jph.12793.
65. Mbili NC, Opara UL, Lennox CL, Vries FA. Citrus and lemongrass essential oils inhibit *Botrytis cinerea* on 'Golden Delicious', 'Pink Lady' and 'Granny Smith' apples. J Plant Dis Prot. 2017;124(5):499-511.
66. El Asbahani A, Miladi K, Badri W, Sala M, Aït Addi EH, Casabianca H et al. Essential oils: from extraction to encapsulation. Int J Pharm. 2015;483(1-2):220-43.
67. Shin J, Na K, Shin S, Seo SM, Youn HJ, Park IK et al. Biological activity of thyme white essential oil stabilized by cellulose nanocrystals. Biomolecules. 2019;9(12):1-14.
68. Wińska K, Mączka W, Łyczko J, Grabarczyk M, Czubaszek A, Szumny A. Essential oils as antimicrobial agents—myth or real alternative? Molecules. 2019;24(11):1-21.
69. Diánez F, Santos M, Parra C, Navarro MJ, Blanco R, Gea FJ. Screening of antifungal activity of 12 essential oils against eight pathogenic fungi of vegetables and mushroom. Lett Appl Microbiol. 2018 ;67(4):400-10.
70. Idris FM, Ibrahim AM, Forsido SF. Essential oils to control Colletotrichum musae in vitro and in vivo on banana fruits. Am Eurasian J Agric Environ Sci. 2015;15(3):291-302.
71. Pedrotti C, Silva Ribeiro RT, Schwambach J. Control of postharvest fungal rots in grapes through the use of *Baccharis trimera* and *Baccharis dracunculifolia* essential oils. Crop Prot. 2019;125: 1-7.
72. Jhalegar MJ, Sharma RR, Singh D. In vitro and in vivo activity of essential oils against major postharvest pathogens of Kinnow (Citrus nobilis × C. deliciosa) mandarin. J Food Sci Technol. 2015;52(4):2229-37.
73. Shao X, Cao B, Xu F, Xie S, Yu D, Wang H. Effect of postharvest application of chitosan combined with clove oil against citrus green mold. Postharvest Biol Technol. 2015;99:37-43.
74. Trabelsi D, Hamdane AM, Said MB, Abdrrabba M. Chemical composition and antifungal activity of essential oils from flowers, leaves and peels of Tunisian Citrus aurantium against *Penicillium digitatum* and *Penicillium italicum*. J Essent Oil Bear Plants. 2016;19(7):1660-74.
75. Wu Y, OuYang Q, Tao N. Plasma membrane damage contributes to antifungal activity of citronellal against *Penicillium digitatum*. J Food Sci Technol. 2016;53(10):3853-8.
76. Grande-Tovar CD, Chaves-Lopez C, Serio A, Rossi C, Paparella A. Chitosan coatings enriched with essential oils: effects on fungi involve in fruit decay and mechanisms of action. Trends Food Sci Technol. 2018;78:61-71.
77. Papoutsis K, Mathioudakis MM, Hasperué JH, Ziogas V. Non-chemical treatments for preventing the postharvest fungal rotting of citrus caused by *Penicillium digitatum* (green mold) and *Penicillium italicum* (blue mold). Trends Food Sci Technol. 2019;86:479-91.
78. Jugreet BS, Suroowan S, Rengasamy RRK, Mahomoodally MF. Chemistry, bioactivities, mode of action and industrial applications of essential oils. Trends Food Sci Technol. 2020;101:89-105.
79. Romanazzi G, Smilanick JL, Feliziani E, Droby S. Integrated management of

postharvest gray mold on fruit crops. Postharvest Biol Technol. 2016;113:69-76.

80. Murmu SB, Mishra HN. The effect of edible coating based on Arabic gum, sodium caseinate and essential oil of cinnamon and lemon grass on guava. Food Chem. 2018;245:820-8.
81. Riva SC, Opara UO, Fawole OA. Recent developments on postharvest application of edible coatings on stone fruit: a review. Sci Hortic. 2020;262:109074.
82. Al-Tayyar NA, Youssef AM, Al-Hindi RR. Edible coatings and antimicrobial nanoemulsions for enhancing shelf life and reducing foodborne pathogens of fruits and vegetables: a review, [*26*, Artic Ahmad le e00215]. Sustain Mater Technol. 2020;26.
83. Choi WS, Singh S, Lee YS. Characterization of edible film containing essential oils in hydroxypropyl methylcellulose and its effect on quality attributes of 'Formosa' plum (*Prunus salicina* L.). LWT Food Sci Technol. 2016; 70:213-22.
84. López-Mata MA, Ruiz-Cruz S, Silva-Beltrán NP, Ornelas-Paz JdJ, Ocaño-Higuera VM, Rodríguez-Félix F, Shirai K. Physicochemical and Antioxidant Properties of Chitosan Films Incorporated with Cinnamon Oil. International Journal of Polymer Science. 2015;1–8.
85. Atarés L, Chiralt A. Essential oils as additives in biodegradable films and coatings for active food packaging. Trends Food Sci Technol. 2016;48:51-62.
86. Talón E, Vargas M, Chiralt A, González-Martínez C. Antioxidant starch-based films with encapsulated eugenol. Application to sunflower oil preservation. LWT. 2019;113:108290.
87. Zhou Y, Zhang L, Zeng K. Efficacy of *Pichia membranaefaciens* combined with chitosan against *Colletotrichum gloeosporioides* in citrus fruits and possible modes of action. Biol Control. 2016;96:39-47.
88. Jesser E, Lorenzetti AS, Yeguerman C, Murray AP, Domini C, Werdin-González JO. Ultrasound assisted formation of essential oil nanoemulsions: emerging alternative for Culex pipiens pipiens Say (Diptera: Culicidae) and *Plodia interpunctella* Hübner (Lepidoptera: Pyralidae) management. Ultrason Sonochem. 2020;61:104832.
89. Liu W, Zhang M, Bhandari B. Nanotechnology–A shelf-life extension strategy for fruits and vegetables. Crit Rev Food Sci Nutr. 2020;60(10):1706-21.
90. Pavoni L, Pavela R, Cespi M, Bonacucina G, Maggi F, Zeni V et al. Green micro- and nanoemulsions for managing parasites, vectors and pests. Nanomaterials (Basel). 2019;9(9):1-31.
91. Xue Y, Zhou S, Fan C, Du Q, Jin P. Enhanced antifungal activities of eugenol-entrapped casein nanoparticles against anthracnose in postharvest fruits. Nanomaterials (Basel). 2019;9(12):1777.
92. Kotronia M, Kavetsou E, Loupassaki S, Kikionis S, Vouyiouka S, Detsi A. Encapsulation of oregano (*Origanum onites* l.) essential oil in β- cyclodextrin (β-CD): Synthesis and characterization of the inclusion complexes. Bioengineering (Basel). 2017;4(3):1-15.
93. Borges DF, Lopes EA, Fialho Moraes AR, Soares MS, Visôtto LE, Oliveira CR et al. Formulation of botanicals for the control of plant- pathogens: a review. Crop Prot. 2018;110:135-40.
94. Vurro M, Miguel-Rojas C, Pérez-de-Luque A. Safe nanotechnologies for increasing the effectiveness of environmentally friendly natural agrochemicals. Pest Manag Sci. 2019;75(9):2403-12.
95. Goncalves D, Ribeiro WR, Menini L. Recent Advances and Future Perspective of Essential Oils in control *Colletotrichum* spp.: A Sustainable Alternative in Postharvest Treatment of Fruits. Food Res Int. 2021;0963-9969.

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