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Review

Spice and herb oil as potential alternative to agrochemicals in postharvest management of fruits and vegetables

Lokesh Muthusamy[1] · R. Balakumbahan[2] · J. Rajangam[3] · S. Sathiyamurthi[2] · T. Anitha[4] · Dharani Muthusamy[5] · T. Velmurugan[3]

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Abstract
Fresh fruits and vegetables are susceptible to several diseases caused by many phytopathogenic microbes which affect their shelf life and quality especially after harvesting. To control these postharvest diseases, the use of synthetic agrochemicals are found to be effective but their phytotoxicity has created a great concern on consumer's health, environment and food security. The continuous application of synthetic agrochemicals have found to be developing resistance to several pathogen populations. Currently, many importing countries enforce strict regulations on the minimal pesticide residual levels in the edible part of fresh produce. All these reasons mentioned above have necessitated to search for the natural and novel formulations as alternatives to replace the conventional chemical application during postharvest treatments. A novel approach to manage the postharvest losses, while retaining the fruit quality, has been implemented by the use of essential oils like cinnamon oil, thyme oil extracted from spices and herbs. This strategy eliminates the need for the use of synthetic formulations, thereby ensuring the global food security. Therefore, this review aims to emphasize the potential use of spice and herb oils as green alternative and as well as protective agents, their mode of action, method of application and their potential challenges by implementing in postharvest management of fruits and vegetables.

Article highlights

- Spice and herb oil emerging as potent food protectants in postharvest management of fruits and vegetables.
- Essential oils are more safer, effective, novel, non-toxicity compared to agrochemicals.
- Promising bio-tool to combat postharvest losses and extending the shelf life of the produce.

Keywords Postharvest management · Herbs · Spices · Essential oil · Greener alternative · Sustainability

✉ R. Balakumbahan, hortibala@gmail.com | [1]Department of Spices and Plantation Crops, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam, Theni, Tamil Nadu 625604, India. [2]Horticultural Research Station, Tamil Nadu Agricultural University, Thadiyankudisai, Kodaikanal, Dindigul, Tamil Nadu 624212, India. [3]Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam, Theni, Tamil Nadu 625604, India. [4]Department of Postharvest Technology, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam, Theni, Tamil Nadu 625604, India. [5]Department of Dairy Chemistry, Verghese Kurien Institute of Dairy and Food Technology, Kerala Veterinary and Animal Sciences University, Thrissur, Kerala 680651, India.

1 Introduction

The growing demand on fresh fruits and vegetables has led the modern agricultural and food industries to opt for more greener solutions instead of usages of synthetic chemicals like pesticides, fungicides, insecticides and food additives on both raw materials and end food products. 85% of Indian population purchase fruits and vegetables from local markets and unorganized sectors, while only 3% was contributed by organized markets [1]. A vast majority of fruits and vegetables are highly perishable and susceptible to postharvest pathogen attack, causing diseases that result in more than 50% of produce being lost from the harvest to final consumer [2] and its postharvest loss can occur at any step of value chain via., harvesting, field handling, packaging, shipping, and storage [3, 4]. It is more prevalent especially in tropical regions due to a lack of cold storage conditions. Vendors use a wide range of agricultural synthetic chemicals to preserve fruits and vegetables till the point of sale in order to resist microbial postharvest illnesses and metabolic activities such as ripening, browning or senescence [5, 6]. The chemicals use might endanger not only human health but also cause environmental concerns [7].

Hence, novel postharvest techniques like ozone treatment [8], UV treatment [9], e-beam irradiation [10], heat treatments [11], cold plasma [12] and stress induction to stimulate defence mechanism of fresh produce [13] are partially replaced or combined with modified and passive atmospheric packaging in order to maintain the freshness of the horticultural crops. Among all these mentioned treatments, use of essential oil (EO) as protective coating in fruits and vegetables was proved to be a promising method in inhibiting the growth of bacteria, fungi and mould [14]; also considerable reduction in change of physical and sensorial attributes. This paper summarizes the potential of spice and herb oil as discussed below (a) Spice and herb essential oils as green alternative to postharvest agrochemicals (b) Mechanism of action of spice and herb essential oil as bio-protectants (c) Novel delivery technique of spice and herb essential oil on fruits and vegetables (d) Potential challenges and advantages in application of spice and herb essential oils as greener alternative and concluding that essential oil from spice and herbs as a promising bio-tool to prevent postharvest losses, thereby contributing to global food security.

2 Spice and herb essential oils as green alternatives to postharvest agrochemicals

Spices and herbs play an indispensable role in medicinal treatments and world cuisines. The crucial chemical compounds naturally present in these spice and herbs as secondary metabolites called bioactives, gives spice and herbs their peculiar characteristics. Extraction of oil concentrates from these crops were termed as Essential Oil (EOs). These are complex lipids made up of an array of volatile and natural bioactive components that are organic and biodegradable. EOs work synergistically to serve as antibacterial, herbicide, insecticide, repellent, antioxidant, fungicide properties, water vapour barrier, flavour, colour barrier, when delivered through various methods of applications either by direct or indirect contact on the surface of food products [15, 16]. The Lippia oil (*Lippia scaberrima*) when applied on citrus fruit, Valencia reduced the incidence of fruit decay by 63% comparing to the agrochemicals, thiabendazole or mixture of guazatine/Imazalil resulted in only 5% and 10% respectively [17]. These EOs are generally regarded as more effective, safer, biorational, eco-friendly with minimal residual effect when compared to the conventional agrochemicals [18]. Certain EOs like basil, juniper, lemongrass, clove, thyme, rose geranium, marjoram, rosemary, celery, sage, oregano, cinnamon, cassia, spearmint, nutmeg, mustard and chamomile are Generally Regarded as Safe (GRAS) which are widely used in agriculture, food, cosmetics and textile industries as recommend by FAO [19].

When compared to conventional methods (steam distillation, hydro-thermal distillation etc.,), non-conventional methods (that utilize high pressure, microwave, pulsed electric filed, ultrasonication, etc.,) provides superior quality, higher yield of oil and protection of heat liable bioactive compounds [20, 21]. By this mean, use of EOs extracted through green technologies may be considered as eco-friendly and sustainable green alternative for agro-chemical and postharvest preservation of fruits and vegetables. Illegal use of banned pesticides and other forms of them (either mislabelled or derived products) should be given high risk priority in agriculture and food industries that affects consumer health. Annual assessment of agro-chemical usage in each country should be reported by National agencies jointly with FAO–WHO to ensure limited use of pesticides that pertains to Sustainable Developments Goals (SDS). EOs also serve as an economic alternative when extracted by using agro- industrial bio-waste like leaves, peels, bark, stems, root and pulp wastes as fuel which can be effectively utilized through green technologies to maintain the integrity of circular and bio-economy.

3 Mechanism of action of spice and herb essential oils

3.1 Antibacterial effect

EOs are basically complex product of polyphenols, terpenes, terpenoids, polypropanes and flavonoids etc., and these components were proved to be effective antibacterial agent, when coated on fruits and vegetables. The mechanism of action involves in sequential reactions between the chemical compound of EOs and bacterial cell membrane. EOs containing citronellol, citral, eucalyptol, eugenol, perillaldehyde, geraniol, carvacrol, linalool, α-terpineol, citronellal, nerolidol, limonene and β-ionone have been reported to have antibacterial effect. The action initiates with penetration of lipophilic terpenes and terpenoids into cell membrane through phospholipid bilayer and disruption of membrane, denaturation of cytoplasmic proteins, change in cytoplasmic osmotic pressure, leakage of cell content, inhibition of ATP energy synthesis, dephosphorylation of membrane simultaneously [22]. Cumin oil inhibited the growth of *Curtobacterium*, *Xanthomonas*, *Erwinia*, and *Agrobacterium* [23], savory oil against *Alcaligenes piechaudii, Bacillus pumilus* in Apple, *Xanthomonas* species in tomato, cabbage and pepper [24], cinnamon oil against bacterial canker disease in kiwifruit [25], EOs from garlic, allspice and basil containing eugenol also displayed antibacterial activity, but the mechanism of action was not clearly defined in defence against *Pseudomonas syringae* sp. in kiwifruit [25, 26] as mentioned in Fig. 1. Recent application of EOs targets pesticide and antibiotic resistant bacteria that results in super bug evolution. The various EOs used, their application on different fruits and vegetables, their mode of actions were discussed in Tables 1 and 2.

3.2 Antiviral effect

Foodborne enteric viruses on surface of fruits and vegetables were scarcely ever reported. The possible route of virus contamination is either through the wet soil that was already contaminated by organic matter like faeces from infected human/animal, polluted water or through postharvest processing steps, where the infected produce come into direct contact. Controlling of virus before harvest is tedious as it involves in many factors [64, 65]. However, by using EOs, few plant viral diseases are reported to be controlled. Oregano oil against tomato leaf curl virus reduced its 10^{-4} disease severity [44], savory oil against tobacco mosaic virus [66], clove against potato leaf roll virus [67] as mentioned in Fig. 1. Due to their irregular and rugged surface, viral adhesion was prevalent. The mechanism is denaturation of glycoprotein in viral cell membrane that acts as the receptors for attachment of virus to the food surface by monoterpenes (α, γ- terpinene, α-pinene, citrol, 1,8-cineole, thymol) from eucalyptus, rosemary and thyme and inhibition of DNA polymerase

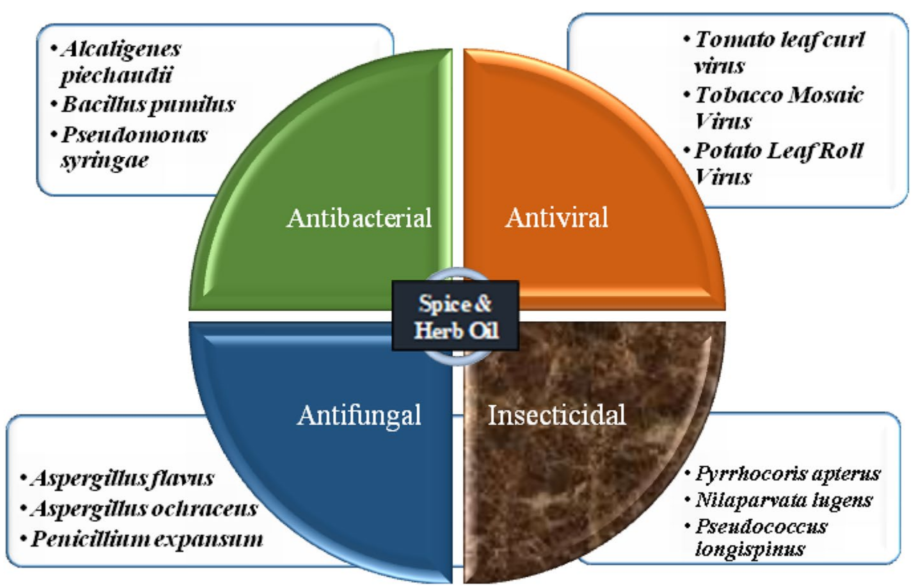

Fig. 1 Various effects of spice and herb oil on the postharvest management of fruits and vegetables

Table 1 Benefits of using spice essential oils in postharvest quality management of fruits and vegetables

Essential oil	Fruits/vegetables	Conjugated with	Method of application	Concentration	Postharvest quality	Outcome	Reference
Black Cumin oil (Nigella)	Loquat fruit	corn starch (2% w/v) and glycerol (0.5% v/v)	Dipping for one hour	0.5%	Delayed ripening and browning incidence	Reduced weight loss and browning, increased antimicrobial activity during 35 days of storage at 4 °C/90–95% RH	[27]
Cardamom oil	Rambutan fruit	10 g palm wood powder paper pad	As box lid	300 µL into paper pad	Increased shelf life	Antifungal protection against mold, shelf life extension up to 14 days at 10 °C/80% RH	[28]
Vanilla oil	Sapota fruit	Chitosan	edible coating- immersion for 60 s	0.6%	Postharvest storage period	Effective oxygen barrier, increased sensorial flavour, increased shelf life up to 7 days at refrigeration condition	[29]
Fennel oil	Valencia Orange	24-epibrassinolide	Dipping for 5 min	600 µL L^{-1}	Overall postharvest quality and delayed ripening	Increased anthocyanins, higher level of sweetness, reduction in weight loss on 45th day, retainment of firmness	[30]
Nutmeg oil	Strawberry	Chitosan based nanoemulsion	Dipping for 30 s	2.5 mL	Increased shelf life and overall quality	Extended antifungal, antimicrobial activity till 5 days at 10 °C	[31]
Clove oil	Table grapes	7% PVA	Injecting into commercial absorbent pad	1%	Increased postharvest quality in cold storage	Antifungal protection and increased shelf life from 9 to 21 days at 13 °C/75% RH	[32]
Ginger oil	Papaya	Carnuba wax and hydroxymethyl cellulose	Nanoemulsion coating	3%	Delayed ripening and increased quality	Oxygen barrier, shelf life extended, colour restoration, less prone to diseases and delayed ripening at 22 °C	[33]
Curcumin oil (turmeric)	Kiwi fruits	Chitosan and cellulose nanofiber	Edible coating	0.05%	Post harvest storage quality	Minimized weight loss, firmness, respiration rate and microbial count till 10 days at 10 °C	[34]

Table 1 (continued)

Essential oil	Fruits/vegetables	Conjugated with	Method of application	Concentration	Postharvest quality	Outcome	Reference
Aniseed oil	Zucchini fruit	Alginate and gelatin	Edible coating	2.55% w/v	Physicochemical and physical properties	Decreased weightloss, chroma, textural damage. Acted as water vapour barrier. Protection against chilling injury	[35]
Dill seed oil	Strawberry	Pure oil	Edible coating	1.5–2%	Post harvest quality in cold storage	Lesser depletion of vitamin C, reduced weight loss and acid production	[36]
Garlic oil	Sweet chilli pepper (*Capsicum annum*)	Chitosan- yam starch	Edible film coating	–	Overall postharvest quality	improvements in physical and mechanical properties, antioxidant and antibacterial activity	[37]
Aniseed oil (Roman)	Mazafati dates	Chitosan and zein	Edible coating	1000 µg/mL	Overall microbial quality in post harvest period	Exhibits higher inhibition activity especially against fungi and bacteria, increased shelf life up to 1 year at 2–4 °C	[38]
Caraway oil	Sweet pepper	Salicylic acid	Foliar Spraying	0.6%	Protection against chilling injury during cold storage	Antifungal activity, increased antioxidative enzyme production, shelf life up to 60 days, retention of colour, firmness and total soluble solids at 4 °C	[39]
Frankincene oil	Green capsicum	Aloe vera and alginate	Edible film coating	6%	Inhibition of senescence	Improved barrier properties like water vapour transmission, UV shielding and antimicrobial activity till 16th day	[40]
Horseradish oil	Tomato	Pure oil	Dipping for 3–5 s	500 µg/mL	Postharvest disease control- Antifungal protection	Controlled mycelium growth, reduced weight loss, colour change, TSS and slow aging	[41]

Table 1 (continued)

Essential oil	Fruits/vegetables	Conjugated with	Method of application	Concentration	Postharvest quality	Outcome	Reference
Betal vine oil (Piper betal)	Tomato	Pure oil	Nanoemulsion edible coating	0.1%	Postharvest quality	Extended shelf life up to 8 days, reduced weight loss, TSS, decay rate and retained lycopene content	[42]
Orange peel oil	Tomato	Chitosan (2%)	Edible coating	100 µL mL^{-1}	Postharvest fungal protection	Shelf life extended up to 8 days at 25 °C and lethal effect towards A. *niger* and *P. citrinum*	[43]
Mint and fennel oils	Yellow zucchini	hydrosols	In vivo assay	–	Insect repellent and antiviral protection	Control over mosaic virus and induced plant defence response towards viral attack	[44]

Table 2 Benefits of using herb oils in the postharvest quality management of fruits and vegetables

Essential oil	Fruits/vegetables	Conjugated with	Method of application	Concentration	Postharvest quality	Outcome	References
Rosemary oil	Mango fruit	2% potassium sorbate (PS)	Edible coating	1000 μL L^{-1}	Inducing defence mechanism against anthracnose incidence	Effective antifungal activity towards incidence of *C. gloeosporioides*, improved texture and sensory qualities	[45]
Lavender oil	Banana	Soybean polysaccharide and carboxyl methyl chitosan	Dipping	–	Post harvest quality	Better moisture barrier, mechanical, thermal properties and delayed browning of skin	[46]
Peppermint oil (Carvacrol)	Baby spinach, romaine, and iceberg lettuce	Emulsified with sunflower lecithin and tween 20	Nanoemulsion dipping	0.75%	Postharvest sanitizing against *E. coli* O157:H7	Effective than chlorine treatment (50 ppm), no chromatic changes till 2 weeks/10 °C	[47]
Marjoram oil	Lettuce	Chitosan and ascorbic acid	Dipping for 60 s	1%	Post harvest quality	Decreased gas production and reduced weight loss	[48]
Eucalyptus oil	Cucumber	Rosemary oil	Vapour and dipping	2:1 ratio	Postharvest quality	Decreased weight loss, no change in texture, vapour method is superior to dipping method	[49]
Spearmint	Carrot, radish, kohlrabis	Pure oil	Coating	500 μL L^{-1}	Postharvest quality	Prolonged shelf life, effective against microbial growth	[50]
Geranium oil	Apples	Pure oil	Coating	1–2 μL/mL	Protection against post harvest decay	Decreased growth of mycelium, lethal action against phytopathogenic fungal species	[51]
Sage Essential Oil	Tomato	Aloe vera (AV)	Edible coating	0.1% sage EO and AV + 0.1% EO	Post- harvest storage quality	Overall post harvest qualities were increased, sensory attributes were unchanged, absence of decay process till 14th day of storage at 11 °C/90% RH	[52]

Table 2 (continued)

Essential oil	Fruits/vegetables	Conjugated with	Method of application	Concentration	Postharvest quality	Outcome	References
Oregano oil	Fresh celery	Inulin and Tween	Nanoemulsion dipping	10%	Postharvest sanitizing against *L. monocytogenes* and *E. coli* O6	Showed restricted activity of microbes and significant reduction in cfu/ml within 60 min of surface treatment	[53]
Rosemary oil	Apple	Water-chestnut starch based nanoemulsions	Edible coating	0.5%	Against *P. expansum*- a blue mould	Antifungal activity till 120 days and lowering the impact of lesion over the surface	[54]
Lemongrass oil	Guava	Chitosan	Edible coating	0.6 µL/mL	Post- harvest storage quality in cold storage	Improvement in post harvest qualities like color, firmness, water vapour transmission and moisture barrier properties till 10th day/12 °C	[55]
Mint oil	Papaya	Chitosan	Immersion coating for 5 min	0.2%	Protection against *Colletotrichum gloeosporioides*	Effective antifungal action, improved post harvest quality observed till 15th day of study	[56]
Basil oil	apple, pear, kohlrabi and potatoes	Pure oil	Gassing	50 ppm	Anti-insect and antimicrobial activity	80% protection from European firebug (*Pyrrhocoris apterus)* and higher anti-microbial activity against *A. chrococcum* and antifungal activity	[57]
Palmarosa oil	Onion	Pure oil	Antifungal assay	0.60 mL/L	Postharvest fungal protection	Inhibition of *Botrytis cinerea* by disruption of cell membrane and complete elimination of pathogen	[58]
Vetiver oil	Banana	bee wax 4 g L^{-1}	Coating	2 g L^{-1}	Protection against fungal disease	Lethal effect against *C. musae,* reduced formation of lesions	[59]
Citronella oil	Grapes	Chitosan, zinc oxide and silver naoparticles	Nanoemulsion edible coating	6.6%	Postharvest quality	Increased shelf life up to 14 days at 20 °C, no skin browning and enhanced antimicrobial activity	[60]

Table 2 (continued)

Essential oil	Fruits/vegetables	Conjugated with	Method of application	Concentration	Postharvest quality	Outcome	References
Savory oil	Banana and tangerine	Zein fiber	Electrospan coating	20% w/v	Postharvest preservation	Inhibited the growth of pathogenic bacteria like *E. coli* and *S. aureus*. Acts as antimicrobial agent	[61]
Thyme oil	Strawberry	Zein fiber	Electrospan coating	4% v/w	Postharvest preservation	Decreased weight loss, antibacterial effect, ability to act as active packaging	[62]
Oils of lemon, sweet orange and grapefruit, and rosemary	Mixed berries	Pure oils	Mixing	0.5%, 0.1%, 0.05% and 0.05% respectively	Postharvest antiviral protection	Effective against hepatitis A, rosemary oil had higher value of reducing viral activity consequently followed by grapefruit oil	[63]

enzyme that replicates its viral particles [68]. Bioactive components from eucalyptus, rosemary and tea-tree oil exhibited higher antiviral activity [69]. EOs and vapours of Linalyl acetate, Linalool, Citronellol, Geraniol, 1,8 –Cineole, α-Thujone, Neral, Terpenyl acetate and Borneol has anti-influenza viral activity [70]. Hence, treating suspected fruits & vegetables or raw material intended to produce high grade quality food products shall be treated with gassing of these EOs vapour as effective virus sanitizing agents. Commercialization of these EOs using spray cans or treating raw materials with EOs using a gas chambers would be possible alternative to prevent contamination of pathogenic viruses during receiving from quarantined locality in households, food industries and local markets.

3.3 Antifungal effect

Fruits and vegetables rich in water content and acidic pH makes them highly vulnerable to fungal attack on prolonged storage. The antifungal mechanism is very similar to antibacterial effect, but due to presence of chitin in their cell wall, there is a higher chance of fungi to transform into resistant fungi by stress signalling induced by chemical fungicides [71]. Use of single fungicide has failed to act against fungal diseases, however by combining chemical fungicides with biocontrol agents have also paved a new application against postharvest fungal control [72]. In potato, combination of oregano and thyme oil against *Fusarium species* was found to be very effective against spore germination with minimum concentration of 3 µL each. Rather as single, combination of both exhibited synergistic effect through lipid peroxidation mechanism [73]. Action against cell permeability modifications, cell membrane and mitochondrial destruction, deregulation of electrochemical proton gradient in plasma membrane, controlled production of nitric oxide synthases (NOS) that increase the resistance of fungi and decreased production of hydrogen peroxide are some of the antifungal effects of EOs. Mycelium growth, biofilm formation and production of extracellular polysaccharide (EPS) are other secondary antifungal effects by EOs. Thyme oil (Thymol) is considered to be most effective antifungal agent, especially towards inhibition of *Aspergillus flavus* (produces mycotoxin called aflatoxin), *Aspergillus ochraceus* and *Fusarium oxysporum* [74, 75]. Other EOs from clove against *Collelotrichum gloeosporioides* [76], *Rhizopus nigricans* and *Penicillium citrinum* [77], oregano against *Rhizoctonia solani* [78], *Aspergillus flavus* [79], cinnamon against *A.niger* [80], *Candida albicans* and *Candida auris* [81], basil against *Aspergillus flavus* and *A. parasiticus* [82], *Candida albicans* [83] and peppermint against *Botrytis cinerea* and *Penicillium expansum* [84] as mentioned in Fig. 1 and destruction of fungal exopolysaccharide [85] also possess considerable effect against fungi. Rather than using single EOs, use of combinations of EOs oil constituting thymol and linanool (from all literature reviewed till 2023) compounds at higher concentration provided promising lethal actions on resistant fungi.

3.4 Insecticidal effect

Insect repellent effect has been studied on various EOs against several individual species of insects. EOs show insect repellent and insecticidal activity at higher concentration. Yet the exact mechanism of insecticidal activity of EOs is still unknown; however, analytical techniques using proteomic revealed that penetration of lipophilic bioactive compounds from EOs into their soft-bodied cuticle, results in disrupting or blocking of their growth hormones, neurotransmitters (GABA-gated Chloride channels) and specific enzymes in their digestive system [86, 87]. Insecticidal activity was due to alteration of RNA and DNA by deregulating ion exchange in mitochondrial region thereby causing death of an organism [88]. Prolonged application of single insecticide have led to the development of resistance against insect-pests. Though, combination of more than one insecticide has greater toxicity to insect-pests, it imparts concern over the residual effects [89]. Kačániová et al., [57] studied that application of basil EO (*Ocimum basilicum*) at 100% concentration acted as insecticidal agent against *Pyrrhocoris apterus*. *Acorus gramineus* (grassy-leaved Sweet flag) oil when applied at 1000 ppm resulted in 100% mortality in female adults of *Nilaparvata lugens* [90]. Applying cinnamon oil at 80 µg/ml caused death of larva of *Pseudococcus longispinus* in guava [91] as mentioned in Fig. 1. EOs obtained from various eucalyptus sp., acts an insecticide, repellant and acaricide against various insect pests and mites like *Blattella germanica, Rhyzoperta dominica, Carpophilus hemipterus, Tribolium castaneum, Sitophilus zeamais, Melophagus ovinus, Lutzomyia longipalpis.* Among the eucalyptus species, *Eucalyptus globus* has higher efficiency in preventing major insect-pest infestation [92]. Hence, EO can be applied alone or by combining with any one of the other EOs or sometimes even with conventional insecticides would be greater option by not only reducing the residual effect but also controlling the insect-pests effectively. Garlic and thyme EOs in combination with synthetic insecticides like cypermethrin and chlorpyrifos performed higher toxicity towards 4th instar larvae of *Spodoptera littoralis* that affects cotton, maize and tomato in Egypt. The EOs synergistically enhanced the activity of cypermethrin in terms of toxicity by inhibiting some detoxifying enzymes that are closely associated to proliferate the pesticide resistance than chlorpyrifos [93]. The practice of using synthetic pesticides. Thus, the application of EOs extracted from spices and herbs would be the greener alternative for synthetic pesticides.

4 Preventative effects of EOs on fruit quality and ripening

The application of vanilla EO in conjugation with chitosan (0.6% conc.) on sapodilla fruit prevented the reduction of fruit weight loss, sugar levels, thereby maintaining the vitamin C levels and extending the shelf life of the fruit upto7 days [29]. The fruit firmness, TSS levels, reduction in fruit weight loss were maintained, when orange, Valencia was treated with fennel EO (600 µL L^{-1}) in combination with 24-epibrassinolide (4 µL L^{-1}). In addition, the combination enhanced the total anthocyanin content, total flavonoid content and improved overall fruit quality [30].The tomato fruits when packed with the sachet filled with the mixture of clinoptilolite clay, activated charcoal and ground clove buds (10:1:1) maintained the fruit remain greener for long period by reducing the ethylene production rate thereby acting an ethylene antagonist. This resulted in delayed ripening by improving the shelf life up to 9 days [94].The nanoemulsion-based coating with ginger EO (18%) on papaya maintained the fruit quality by retarding the fruit weight loss, improving flesh firmness, peel color and delayed the fruit ripening by reducing the respiration rates, resulting in shelf life extension up to 9 days on storing at 22 ℃ [33]. To summarize the effect of EOs on fruit quality and ripening, the overall fruit quality was improved compared to the control, when EOs are applied at optimum level. Hence EOs are considered to be one of the promising bio-tool to maintain the fruit quality and delay ripening without or least affecting its sensory attributes.

5 Novel delivery technique of spice and herb EOs on fruits and vegetables

Effectiveness of application of EOs depends upon the method of delivering bioactive compounds on fruits and vegetables. This depends on the several external factors like storage temperature, concentration of EOs, modes of delivery, humidity and environmental exposure and internal factors like intracellular space, thickness of epidermis, texture of the product and pest infestation before harvest. These essential oils can be delivered through conventional methods (spraying, dipping, coating, fumigation, injection) and non-conventional methods (nanotechnology, microbubble technology, electrospun coating, hydrosol, fruit stalk delivery) discussed in Tables 1 and 2. These non-conventional methods are regarded as the novel methods as each of these methods are effective with various advantages.

5.1 Nanotechnology

Advances in nanotechnology introduced various field of application in food and agricultural industry. Nano-emulsion, nano-spray, nano-coating, nano-fibers, edible film with nano-emulsified EOs and nano-particles are diverse output of nanotechnology. Several technology can be used to prepare nano-emulsion and particle like spray-drying, freeze-drying, electrospinning and other green technologies like ultrasonication, microfluidization, cold plasma etc. EOs in their nanoform has higher stability against oxidation, increased bioefficieny, water soluble, higher penetration rate and sustained release of bioactive compounds on application [30]. Peppermint oil as nano-emulsion dipping on Baby spinach, romaine and iceberg lettuce [47], Oregano oil as Nano-emulsion dipping on fresh celery [53], ginger oil on papaya [33], betal vine as nano-emulsion edible coating on tomato [42], Citronella oil as Nano-emulsion edible coating on grapes [60] were some reported nano-emulsified EOs application in postharvest quality preservation technique discussed in Tables 1 and 2.

5.2 Microbubble technology

This technique uses ozone (O_3) as natural fumigant and effective able to clean the fruits and vegetable surface matrix through cavitation process that oxidizes the contaminates, agro-chemical residues and surface cleaning dirts. Microbubble (MCB) technology is one of the emerging technology used to clean food surfaces, decontamination of food products and to prepare reduced fat oil dispersion. This MCB can be exploited for cleaning combined with EOs for fruits and vegetables to perform removal of pesticide residue and to ensure even coating of bioactive compound through gas–liquid mass transfer [95]. Incorporation of MCB into EOs produces stable oleoforms in the presence of stabilizer that offer wide range of advantages like reduced oil dispersion, efficient coating [96]. Hence, in future MCB would be able to produce dry EOs dispersion or EOs Pickering emulsion to preserve postharvest quality of raw materials.

5.3 Electrospun coating

"Electrospun coating" generally refers to a process known as electrospinning, which is a technique used in the fabrication of nano-fibrous materials. Electrospinning involves the use of an electric field to create a charged jet of polymer solution or melt that is drawn towards a grounded or oppositely charged collector. The process results in the formation of ultrafine fibers that can be deposited on a substrate to form a coating [97]. Such technology can be used as delivery method for EOs as postharvest quality preservation technique. Some of the notable examples are zein fiber loaded savory and thyme EOs acted as antimicrobial against pathogenic microbes and also prevented postharvest physico-chemical losses productively [62, 63].

5.4 Hydrosol

A hydrosol, also known as floral water or plant water, is a co-product of the process of steam distillation or hydrodistillation used in the production of essential oils. When plant material, such as flowers, leaves, or herbs, is subjected to steam or water vapor, the essential oil is released from the plant material. The vapor then condenses, resulting in two products: the essential oil and the hydrosol. Although hydrosol has limited bioactive components compared to EOs, but has certain advantages like higher water dispersibility, cheaper price and able to perform similar action like EOs [98]. Hydrosols from *Teragonia spicata* [99], lemongrass [100], mint and fennel [44] achieved antibacterial, antiviral, insect repellent and antioxidative effects. Utilization of hydrosol not only reduces the cost of production, but also contributes significantly to circular bio-economy [101].

5.5 Fruit-stalk delivery

Fruit-stalk delivery is a novel strategy for delivering supplementation and preservatives by either injection or bagging of stalk of the fruit for certain period. The stalk of the fruit or vegetable acts as a source of amino acids in kiwifruit, mineral pool in broccoli heads. However, when the stalk of the chilli is removed, it fastens the rate of decaying [102]. So, the stalk acts as a portal to the inner fruit part. One of the study by Song et al. [103], experimented application of nano-capsules with calcium, chitosan and alginate complex to stalk of apple enhanced the calcium absorption with response to release of citric acid in fruit that greatly prevented bitter pit defect compared to other method of delivery. This novel method of delivery would be great alternative rather than dipping, spray or coating that requires lesser concentration of EOs and better performance.

6 Potential challenges in application of spice and herb EOs in fruits and vegetables

6.1 Over dosage of EOs

EOs at low concentration acts as protective shield against browning, bacteria, fungi and virus, but at higher concentration affects the natural biological process of the fruits and vegetables. Only few studies have reported the overdose of EOs in plants. EO blend of thyme, mint, lemon and lemongrass in cucumber plant at optimal dose (2.5 mL/L) prevented the powdery mildew; but, increased dose of 3.0–4.0 mL/L produced shiny spots on plant leaves and further increase in dose up to 5.0 mL/L eventually caused death of the plant [104]. Consumption of higher dose of EO coated raw material also adversely affect the human health from mild to advanced condition on prolonged exposure [105, 106]. Similarly higher dosage of EOs to the softer surface of fruits and vegetable inhibits the respiration rate due to their hydrophobicity by blocking the cuticle in epidermis. Higher dose of sage EO (0.5%) decreased total soluble solids, β-carotene and acidity of tomato [52]. The surface appears to be oily, slippery which make them difficult to handle. Hence, optimal level of EO formulation with water soluble ingredients should be used as preservative agent in fruits and vegetables.

6.2 Change in sensory attributes

One of the notable disadvantage of EO application in food products was their strong influence on organoleptic properties. As the bioactive compounds in EOs are highly aromatic, even at low level adversely affects the sensory attributes of final treated produce. Oregano and thyme EOs washed lettuce resulted in sharp acidic taste and strong chemical aroma, that flavour and taste of the washed lettuce was completely unacceptable [107]. Higher dose of sage EO (0.5%) has negative impact on chroma, lycopene and redness of tomato [52]. Masking of strong aroma of EOs can be achieved by right formulation with masking agents like maltodextrin, β-cyclodextrin and EDTA (Ethylene diamine tetra acetic acid).

7 Conclusion and future trends

This review has aimed to report on the use of spice and herb oil, either alone or in conjunction with other materials, to develop a sustainable food protectants alternative to the agrochemicals. Approaches incorporating the spice and herb essential oils have been regarded as potent natural antimicrobial agents in fruits and vegetables. Food security has become a critical global concern, and the implementation of essential oils as bio-protectants through different coating techniques holds significant potential for mitigating the postharvest losses due to contamination and upholding the food security.

Therefore, by incorporating the spice and herb EOs as a combating plant based food protectants into marketing practices, there is a notable opportunity to substantially decrease the risk of pathogenic contamination and prolong the shelf life of fruits and vegetables. However, further experimental trials and detailed examinations are needed to be carried out to understand the biological activity, physiological function, inhibitory action and dispersion of each spice and herb essential oils and their bioactive compounds in fruit and vegetable tissues, thereby ensuring to develop a novel formulation that is safe for the environment as well as human health.

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