

Review

# Potentials of Medicinal Plant Extracts as an Alternative to Synthetic Chemicals in Postharvest Protection and Preservation of Horticultural Crops: A Review

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**Abstract:** Horticultural crops undergo various physiological and biochemical changes that lead to undesirable physiological disorders, decay and subsequent economic losses during storage. Quality degradation of horticultural crops is mainly caused by postharvest pathogens such as *Botrytis cinerea* and *Penicillium* spp., etc. The application of synthetic fungicides remains the most effective method to control postharvest pathogens. However, their use is becoming increasingly restricted internationally due to health concerns and consumers' requests for safe and natural alternatives. This has led researchers to investigate natural flora as one of the alternatives to be used in crop protection and preservation. Various medicinal plant parts have different phytochemicals and antioxidants that can be used in crop protection and preservation. Extracts from plants such as *Ruta chalepensis*, *Eucalyptus globulus*, etc., have proven to be effective in controlling postharvest pathogens of horticultural crops and increased their shelf life when used as a substitute for synthetic chemicals. Furthermore, extracts from neem and other medicinal plants contain a predominant and insecticidal active ingredient. The application of medicinal plant extracts could be a useful alternative to synthetic chemicals in the postharvest protection and preservation of horticultural crops. This review paper details the application of medicinal plant extracts for postharvest protection and preservation of horticultural crops.

**Keywords:** natural preservatives; indigenous knowledge; food security; quality degradation; economic losses



**Citation:** Nxumalo, K.A.; Aremu, A.O.; Fawole, O.A. Potentials of Medicinal Plant Extracts as an Alternative to Synthetic Chemicals in Postharvest Protection and Preservation of Horticultural Crops: A Review. *Sustainability* **2021**, *13*, 5897. <https://doi.org/10.3390/su13115897>

Academic Editor: Dario Donno

Received: 27 April 2021

Accepted: 20 May 2021

Published: 24 May 2021

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## 1. Introduction

Medicinal plants have been the basis of the treatment of various diseases in African traditional medicine and other forms of treatment from diverse cultures of the world [1–3]. Despite the well-documented ethnobotanical literature, very little scientific information is available on the efficacy and phytochemistry of indigenous medicinal plants and plant extracts in postharvest protection and preservation of horticultural crops [4,5]. In contrast with countries such as China and India, the use of medicinal plants and plant extracts in Africa is greatly underdeveloped for crop protection and preservation [2,3]. Countries such as China, India, Japan, Brazil, Mexico, South Africa, Kenya, Morocco, Tunisia and Egypt are major international role players in the production and export of fresh produce globally [6]. However, these horticultural crops are highly perishable and do experience various physiological and biochemical changes which lead to the development of undesirable physiological disorders and quality degradation, leading to major economic losses [7–9]. Fungal infections are the major causes of postharvest losses of fresh fruits and vegetables either in transit or storage [10]. They cause significant economic losses in the commercialization phase and are rendered unfit for human consumption [7–10].

About one-third of the food produced in the world per year for human consumption is lost or wasted [11]. In Africa, postharvest losses of fruit and vegetables could be as high as 70%, while the global quantitative food losses and wastes during the year are around 40–50% for fruits and vegetables only [12]. Every year, consumers in developed countries lose almost as much food (over 220 million tons) as the total net food production in sub-Saharan Africa (around 230 million tons) [13]. Not only are losses a waste of food, but they also represent a similar waste of human effort, farm inputs, livelihoods, investments and scarce resources such as water [13,14]. Some of the major causes of these postharvest losses are physical damage, poor handling, transportation and storage, poor packaging, postharvest pathogens (*Rhizoctonia solani*, *Alternaria alternata*, *Colletotrichum gloeosporioid*, *Penicillium digitatum* and *Botrytis cineria*) and senescence [11,12]. The horticulture industry relies on the use of capital-intensive technologies during the postharvest phase of production and fungicides are also applied to reduce the losses due to postharvest diseases or decay [15–17]. However, there is a growing global concern about the use of fungicides. The use of synthetic chemicals is becoming increasingly restricted locally and internationally due to health concerns and consumers' requests for safe and sustainable natural alternatives. As a result, the commercial success of the horticulture industry is threatened [10,11,18,19].

Crop protection and preservation are central entities in global food sustainability and security [20,21]. Several methods of preservation have successfully prohibited food waste caused by insect infestation, environmental conditions and microbial attacks [20,21]. However, studies have revealed vast health issues relating to applications of synthetic pesticides and preservatives in crop protection and preservation [22]. This has prompted the exploration of safe and cost-effective constituents without harmful or detrimental effects to the health of consumers and the environment at large [23]. Natural preservatives and pesticides have been formulated and applied in food, pharmaceutical and agrochemical industries [23–26].

A wide range of phytochemicals such as alkaloids, cyanogenic glycosides, phenylpropanoids, polyketides, anthocyanins, carbohydrates, amino acids, lipids, nucleic acids, terpenoids, flavonoids, phenols, saponins and tannins found in most medicinal plants are essential materials in the production of several pesticides and fungicides that can be helpful in crop protection and preservation of horticultural crops [2,27–30]. For example, the antimicrobial and antioxidant properties of the medicinal plant extracts have been attributed but not limited to phytochemicals such as citral, aspilactonol B and 8-methyl-6-prenylquercetin found in *Cymbopogon citratus* [31], fukugetin and fukugiside found in *Geophagus brasiliensis* [31] and carnosic acid, carnosol and rosmanol found in *Lepidium meyenii* [32]. Therefore, there is a need to undertake different phytochemical analysis (active ingredients, nutritional and mineral content), biological activities (e.g., antimicrobial, anti-inflammatory and antioxidant) and safety evaluation (cytotoxicity and genotoxicity) of medicinal plants as a substitute for synthetic pesticides and fungicides to be used in protection and preservation of horticultural crops [4,33,34].

Regular monitoring of the pest population dynamics in agroecosystems can reveal the economic losses and importance of a particular pest which can be mitigated by medicinal plant extracts [35,36]. Despite the relatively low rates of expansion of botanically based pesticides, regulatory changes in many parts of the world are driving a renaissance for the development of new natural pest control products that are safer for human health and the environment [37,38]. Therefore, botanical pesticides can help provide new ideas for the development of new pest management products [39,40]. Hundreds of indigenous and exotic species with insecticidal properties have been reported around the world through various farmer surveys and subsequent research, many of which have been confirmed to be active against a wide range of arthropod pests [39,40]. On-farm use of insecticidal plants, particularly among resource-poor smallholder farmers, is widespread and familiar to many African and Asian farmers [38–40].

By 2015, more than 400,000 plant species had been identified, a majority of which are flowering plants (369,000), and each year nearly 2000 others are discovered [41,42].

These plants produce a needed wide range of primary and secondary metabolites that have antibacterial and antifungal properties [43–45]. Several medicinal plant extracts such as neem (*Azadirachta indica*) leaf extract [46], turmeric (*Curcuma longa*) leaves [47] and lemongrass extracts (*Cymbopogon citratus*) [48] have been successfully applied as fungicides. The activity of neem leaf extract can be attributed to the presence of compounds such as dibutyl phthalate, phytol, nonanoic acid, tritriacontane and 1,2-benzenedicarboxylic acid in the crude extracts [46]. Studies have shown that some plants produced secondary metabolites, such as essential oils and volatile compounds that can have a biocidal action against postharvest pathogens [49,50]. Commercial products of natural fungicides such as rosemary oil, neem oil, *Aloe vera* gel (AVG), tea tree oil and jojoba oil, among many others, are now used in crop protection and preservation as fungicides [51–53], while commercial natural insecticides include nicotine and pyrethrum, amongst others [54,55]. Medicinal plant extracts could be a useful alternative to synthetic fungicides in the control of rot fungi when handling fruits and vegetables after harvest. This review detailed the various scientific evidence to support the potential of medicinal plant extracts for postharvest protection and preservation of horticultural crops.

## 2. The Renaissance of Medicinal Plants as Antimicrobial Agents in Postharvest Preservation

The possibility to control many postharvest pathogens using medicinal plants has been investigated on a wide range of horticultural crops [56,57]. In modern agriculture, the application of synthetic fungicides remains the most effective and common method to control postharvest rot of horticultural crops [57,58]. However, increasing requests by consumers for fresh produce that is free of fungicide residues has contributed to the interest of researchers in the development of alternative methods for controlling postharvest decay of fresh produce [59,60]. Increasing health hazards such as the development of cancer, infertility and effects in the offspring of pregnant women caused by the application of postharvest fungicides have led to their restriction in some commodities or total ban in organic agriculture [61,62]. In the last 10 years, the Pesticide Action Network International has banned the use of many highly hazardous pesticides for use in agriculture (Table 1).

**Table 1.** Pesticide Action Network (PAN) International selected list of highly hazardous pesticides (2021) for use in agriculture in the last 10 years [62].

Chemical	Application	Classification of Pesticides	Year of Ban
1,2-dibromoethane	It is used as a soil fumigant to control nematodes and other soil pests in crops such as vegetables, ornamentals, pineapples and tobacco	Classified as a probable carcinogen by the US EPA	2010
Ethylene dibromide	It is used as a fumigant to protect against insects, pests and nematodes in citrus, vegetable and grain crops	Classified as a probable carcinogen by the US EPA	2010
Hydrogen cyanide	It is used in the treatment of citrus and other fruits for the control of scale insect and thrips, in quarantine treatments of bananas, pineapple and other commodities for the control of aphids, mealybugs and other exposed insects. It is also used in a vacuum treatment for bulbs, rhizomes, tubers, asparagus roots and strawberry plants to control certain mites and nematodes	Classified as “fatal if inhaled” (H330) according to the EU GHS.	2010
Lindane	An insecticide used to control a broad spectrum of insects in fruits and vegetables	Classified in several categories, and in 2018, IARC classified it as “Carcinogenic to humans”	2010

Table 1. Cont.

Chemical	Application	Classification of Pesticides	Year of Ban
Metaflumizone	It is used to control the diamondback moth on Brassica leafy vegetables	Is very persistent in the water-sediment environment and the bio-concentration factor is over 5000. It is classified as P = Persistent and B = Bio-accumulative	2010
Noviflumuron	Prevents the successful molting and development of subterranean termites and eventually eliminates the colony that can cause damage to fruit tree plantations It is used to control blights, rots and molds in vineyards and on raspberries, lettuce, kiwi, snap beans and onions. It is also used to protect crops against <i>Botrytis cinerea</i> and <i>Sclerotinia sclerotiorum</i>	Classified as a probable carcinogen by US EPA Annual Cancer Report and classified as WHO Class 1a	2010
Vinclozolin	It is used to control powdery mildew in cucurbits, rust on cereals and apple scab	Classified as a reproductive toxicant and endocrine disruptor	2010
Cyproconazole	It is used as an acaricide and insecticide on citrus, grapes, pome fruit, stone fruit and tree nut crops	Classified as presumed human reproductive toxicant according to EU GHS Classified as a probable carcinogen by the US EPA and is now also classified as "Carc 1B" by the EU GHS	2011
Ethiofencarb	It is used as an insecticide in controlling aphids on hard and soft fruits and some vegetables It is used as a broad-spectrum insecticide that inhibits cholinesterase activity. It is used in vegetables, fruit crops, cereals and orchard crops for the control of a wide range of insect species	Classified as WHO Class 1b	2012
Methomyl	It is used for pre-emergence weed control on the potato and also to defoliate seed or root crops for pre-harvest desiccation	Classified as WHO Class 1b	2015
Diquat	It is used as a herbicide for pre- and post-emergence control of susceptible weeds on fruit orchards, vegetables and other field crops	Classified as a probable carcinogen by the US EPA and is now also classified as "Carc 1B" by the EU GHS	2016
Flumioxazin	It is used to prevent sucking insects such as aphids, leafhopper, whitefly and <i>Lygus sp.</i> on citrus, pome and stone fruits, tree nuts, grapes, coffee, cocoa and leafy vegetables	Classified as a reproductive toxicant	2016
Flupyradifurone	It is used to control aphids, red spider mites, mealybugs, thrips, scales and whiteflies on ornamentals, fruits and vegetables	Highly toxic to honey bees (oral LD <sub>50</sub> ) and aquatic life	2016
Malathion	It is ethylene (bis) dithiocarbamate fungicide used in the control of early and late blights on potatoes and tomatoes and many other diseases of fruits, vegetables, field crops and ornamentals	Classified as a probable carcinogen by the US EPA and is now also classified as "Carc 1B" by the EU GHS	2016
Maneb	It is used to control aphids, brown planthopper and whiteflies in field vegetables, ornamentals, deciduous fruit and citrus	Classified as an endocrine disruptor	2016
Pymetrozine	Used as a selective post-emergence control of annual and perennial grass weeds in potatoes, soya beans, sugar beet, peanuts, oilseed rape, sunflowers, vegetables, cotton and flax.	Classified as a probable carcinogen by the US EPA and is now also classified as "Carc 1B" by the EU GHS	2016
Quizalofop-p-tefuryl		Classified as an endocrine disruptor (EDC)	2016

Table 1. Cont.

Chemical	Application	Classification of Pesticides	Year of Ban
Thiram	It is used to control stem gall of coriander, damping-off on allium crops and neck-rot of onion	Classified as toxic to aquatic zooplanktons	2016
Zineb	It is used as a broad-spectrum fungicide to control the scab in apples and pears, leaf curl in peaches and anthracnose and early blight in tomatoes	Classified as an endocrine disruptor	2016
Ziram	It is used as a broad-spectrum-use fungicide to control scab in apples and pears, leaf curl in peaches and anthracnose and early blight in tomatoes, controlling leaf blight and scab in almonds, shot-hole in apricots, brown rot and leaf spot in cherries, scab and anthracnose in pecans and leaf spot, rust and powdery mildew in ornamentals	Toxic to aquatic zooplanktons	2016
Propiconazole	In bananas, it is used to control <i>Mycosphaerella musicola</i> and <i>Mycosphaerella fijiensis</i> var. <i>difformis</i> ; in coffee, it is used against <i>Hemileia vastatrix</i> ; in stone fruits, it is used against <i>Monilinia</i> spp., <i>Podospaera</i> spp., <i>Sphaerotheca</i> spp. and <i>Tranzschelia</i> spp.; soft rot on stone fruits	Classified as presumed human reproductive toxicant according to EU GHS	2018
Propineb	It is used to control apple scab, leaf and fruit spots on pomegranate, control chili die-back and buckeye rot on tomato	Classified as a probable carcinogen by the US EPA Annual Cancer Report	2018

The most commonly used fungicides in postharvest preservation of horticultural crops are azoxystrobin, fludioxonil, imazalil, pyrimethanil and thiabendazole, which are synthetic compounds with different modes of action that can be applied either in waxes or water [63,64]. However, the overuse of fungicides and pesticides in agriculture is now a public concern because of the harmful potential these substances have in the environment, and the food chain represents a risk for human health [61,62]. Moreover, the overuse of these synthetic fungicides has resulted in the emergence of resistant strains of pathogens and this has become a major global problem because the frequency of mutant phenotypes in the populations is high [65,66]. Some of these fungicides are suspended because of their high toxicity, and there is increased pressure on the food value chain to either remove these agents or to adopt natural alternatives for the maintenance or extension of a product's shelf life [67]. Such obstacles provide new opportunities for those seeking natural alternatives for new preservatives to be applied on horticultural crops. The control of postharvest diseases in fruits and vegetables using synthetic chemicals is associated with several hazardous effects (Table 2).

**Table 2.** Common control of postharvest diseases in fruits and vegetables using synthetic chemicals and their hazardous effect on human health.

Disease	Crop Affected	Symptoms	Control	Reference	Hazardous Effect According to PAN [62]
Anthracnose	Apples	Black spots appear on skin of the affected fruits which gradually become sunken and coalesce.	Before storage, treat with hot water (50–55 °C) for 15 min or dip in benomyl solution (500 ppm) or thiobendazole (1000 ppm) for 5 min. Prune and destroy infected twigs and spray carbendazim or thiophanate methyl (0.1%) or chlorothalonil (0.2%) on a fortnightly interval during the rainy season.	[68]	Can affect the reproductive system in males
Stem end rot	Avocado	The affected area enlarges to form a circular, black patch around the base of the pedicel. The pulp becomes brown and softer during storage.	Careful handling of potatoes without causing any wounds and dipping the potatoes in aureofungin-sol at 500 ppm for 20 min to control infection in storage.	[69]	Can cause infertility and destroy the testicles
Soft-rot	Potato	Young spots start from the stem end of the fruit as light brown watery rot. As the fruit ripens, area of the rotting increases, and the skin becomes wrinkled. A peculiar musty odour is later emitted.	Treatment with mancozeb to check the disease in storage.	[70]	Highly carcinogenic
Bitter-rot	Apple	Faint, light brown discolouration beneath the skin develops. The discolouration expands in a cone shape. The circular, rough lesions become depressed. Pink masses of spores are found arranged in defined rings.	Postharvest sprays with imazalil, azoxystrobin, fludioxonil or mixtures of these may provide control.	[71]	Has detrimental effects on the nervous system and should be used with caution.
Alternaria rot	Stone fruits	Alternaria rot is characterized by circular, dry, firm, shallow lesions covered with dark, olive green to black surface mycelial growth. The infected tissue is brown, such as that caused by brown rot.	A pre-harvest spray of pyraclostrobin or fludioxonil will give some control.	[72]	Can cause developmental effects in the offspring of pregnant women
Botrytis rot	Brinjal	The fruits show water-soaked and softened tissue. The water-soaked spots are irregular in shape and are approximately 25 mm in diameter. The fungus that develops on the surface of the fruit shows a dark grey growth.	Use postharvest fungicides such as benomyl, fenbuconazole and fludioxonil.	[73]	Can cause eye injury and skin irritation
<i>Rhizopus stolonifer</i>	Banana	The infection starts as a circular tan area around an island of fruit. The skin will slip off from the flesh if you put slight pressure on it. Next, the fluffy white growth of the fungus becomes visible near the centre and rapidly colonizes the whole area.		[74]	Longer exposure can result in severe liver damage

Table 2. Cont.

Disease	Crop Affected	Symptoms	Control	Reference	Hazardous Effect According to PAN [62]
<i>Penicillium italicum</i>	Citrus	Early symptoms include a soft water-soaked area on the peel, followed by the development of a circular colony of white mould. Bluish asexual spores (conidia) form at the centre of the colony, surrounded by a broad band of white mycelium. The fruit rapidly spoils and collapses, with sporulation sometimes occurring internally.	Add sodium bicarbonate to either imazalil, thiabendazole, pyrimethanil or fludioxonil for improved performance.	[75]	Exposure to these chemicals can have negative effects on the respiratory system and they are known to be a carcinogen
<i>Penicillium digitatum</i> Sacc.	Citrus	Symptoms include a soft water-soaked area on the peel, followed by the development of a circular colony of white mould, up to 4 cm in diameter. Green asexual spores (conidia) form at the centre of the colony, surrounded by a broad band of white mycelium.	Add sodium bicarbonate to either imazalil, thiabendazole, pyrimethanil, or fludioxonil for improved performance.	[75]	Exposure to these chemicals can have negative effects on the respiratory system and they are known to be a carcinogen
Brown-rot	Stone and pome fruits	The infection of the fruit usually occurs as the fruit approaches full ripeness. A rapidly spreading firm brown rot develops, and the fungus produces masses of fawn-coloured spores often in concentric zones. Infected fruit shrivels to a 'mummy'. Brown rotted fruit in cold storage appear black and there may be no signs of sporulation	Spray with fungicides such as Merivon, Luna Sensation and Fontelis.	[76]	Highly toxic to beneficial insects such as bees
Sour-rot	Citrus	Lesions often occur near the stem-end scar, are water-soaked and may have a white scummy growth in the cracks. The odour of these lesions is distinctive and is similar to that produced by lactic acid bacteria	The use of guazatine is effective in controlling this disease, while SOPP results in some protection.	[75]	Can cause skin cancer

The international community has taken several important initiatives to protect the environment and people's health from chemicals. These include the Montreal Protocol on the protection of the ozone layer, the Basel Convention on the Transboundary Movement of Hazardous Wastes, the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, the Stockholm Convention on Persistent Organic Pollutants and the Strategic Approach to International Chemicals Management [62]. Initiatives are being led by governments and non-governmental organisations (NGOs) for improving pesticide and crop protection policies towards safer, socially just, environmentally sustainable and economically viable pest management systems [61,62].

Medicinal plants have been used for thousands of years to treat human health disorders and prevent diseases. These medicinal plants have bioactive compounds that can be considered as good alternatives to synthetic antimicrobial and antioxidant preservatives in horticultural crops [77–80]. Results from several publications in the last two decades show that compounds derived from plants and their antimicrobial and antioxidant capacity tested both *in vitro* and *in vivo* gave positive results and are a viable alternative to the use of synthetic chemicals [2,15,81,82].

### 3. Medicinal Plant Extracts against Pathogens in Horticultural Crops

Although there is an array of indigenous floras in tropical, semi-arid and humid regions currently used worldwide for human medical or treatments, only a few of them have been studied for their use in protecting horticultural crops against pathogen infection [83]. Indigenous knowledge has already identified medicinal plant extracts as traditional means to control plant diseases [77,80]. The application of these medicinal plant extracts in controlling postharvest pathogens of horticultural crops has become an important field of study [78]. The family of higher plants and shrubs, particularly, tropical flora, has been shown to provide a potential source of naturally produced inhibitory chemicals [77]. The natural product of medicinal plant extracts such as volatile chemicals, essential oils and phenolic compounds has been applied successfully to control postharvest diseases of stored fruits and vegetables [84–86]. Documented medicinal plant extracts for use in indigenous knowledge (IK) or used in the modern day as alternatives for synthetic chemicals for crop protection and preservation are summarised in Tables 3 and 4.

Table 3. List of commonly used medicinal plant extracts used as pesticides.

Plant Name	Country of Origin	Plant Part Used	Focus of the Study	Treatment Application	Key Findings	Reference
<i>Azadiracta indica</i>	India	Aqueous leaf extracts	To control <i>Pieris brassicae</i> on cabbages	Aqueous concentration (10, 5, 2.5 and 1.0%) were sprayed on cabbage foliage.	At 5%, had an anti-feedant of 82.5%. The anti-feedant effect of the different concentrations decreased with a decrease in concentration. The anti-feedant activity was in ascending order with an increase in concentrations. The leaf area consumed was highest at 1158.6 + 254.79 cm <sup>2</sup> at 2% concentration in 5th instar, and it was lowest at 8% concentration in the 1st instar larva as 92.2 cm <sup>2</sup> . The anti-feedant of 87.5% over control was attained in 3rd instar larva at 8% concentration, while it was lowest as 22.74% in the 2nd instar larva at 2% concentration.	[87]
<i>Azadiracta indica</i>	India	Kernel aqueous extract	Control red slug caterpillar on tea plants	Tea leaves were sprayed with different neem kernel aqueous extract (NKAE) concentrations at 2, 4, 6 and 8%.		[37]
<i>Bobgunnia madagascariensis</i>	Senegal	Dried pods	Aqueous extracts dried pods in controlling ladybird beetle on <i>Brassica napus</i>	Aqueous extracts applied separately at 5, 10, 15, 20 and 25% w/v under laboratory conditions. The mortality of <i>H. variegata</i> was recorded 24, 48 and 72 h post-exposure.	<i>B. madagascariensis</i> (25% w/v) caused the highest mortality (90%).	[88]
<i>Lippia javanica</i>	Botswana	The essential oil of leaves	To control <i>F. graminearum</i> in sweet corn	The bioassays were carried out at concentrations of 0.87, 0.65, 0.43, 0.22, 0.11, 0.054 and 0.027 mg mL <sup>-1</sup> (essential oil mL <sup>-1</sup> ).	The maximum antifungal activity was recorded from the concentration of 0.87 g mL <sup>-1</sup> , and the least activity was recorded for the least concentration of 0.027 g mL <sup>-1</sup> . After the 3rd day, the inhibition zone for 0.87 g/mL was larger (25.00 mm) while 0.027 g/mL had the smallest inhibition zone (3.33 mm). After 14 days, 0.87 g/mL had an inhibition zone of 7 mm while 0.027 g/mL had 0 mm.	[89]

Table 3. Cont.

Plant Name	Country of Origin	Plant Part Used	Focus of the Study	Treatment Application	Key Findings	Reference
<i>Lippia javanica</i>	Botswana	Leaf powder	Control mustard rape aphids and tomato spider mites on tomatoes	Plant extracts from leaf powder at 12.5% <i>w/v</i> were mixed with 0.1% <i>v/v</i> soap. The treatments were applied 24 h post mixing the plant materials with water at a rate of 1 L on an area of 5 m <sup>2</sup> using a knapsack sprayer fitted with a hollow cone spray nozzle.	Plant extracts from leaf powder at 12.5% <i>w/v</i> using 0.1% <i>v/v</i> soap can be used against rape aphids and tomato spider mites. <i>L. javanica</i> at 12.5% reduced aphids by 83% and 75.9% tomato mites.	[90]
<i>Melia azedarach</i>	India	Aqueous leaf extracts	Control <i>Pieris brassicae</i> on cabbages	Aqueous concentration (10, 5, 2.5 and 1.0%) was sprayed on cabbage foliage.	At 5%, had an anti-feedant of 88.3%. The anti-feedant effect of the different concentrations decreased with a decrease in concentration.	[87]
<i>Melia azedarach</i>	India	Leaves plant powder	To control cucumber pests	Crushed fruits of <i>M. azedarach</i> , were tested at the rates of 30 and 60 g kg <sup>-1</sup> , Bitter apple extract (BA) was mixed with distilled water to obtain BA fruit concentrations (30, 60 and 90 mL L <sup>-1</sup> ) The treatments were mixed with 3, 6 and 12 g of sugar, respectively.	All the concentrations were effective in controlling 90% of pests than the control	[91]
<i>Solanum incanum</i>	Madagascar	Fruits were used as a paste	To control cabbage aphids	Kale was routinely sprayed with 10, 25, 50 and 75% <i>S. incanum</i> extract.	The concentration of 90 mL L <sup>-1</sup> had the highest mortality of cabbage aphids, and the cabbages had a good appearance.	
<i>Solanum incanum</i>	Madagascar	Aqueous crude fruit sap extract	To control green peach aphids ( <i>Myzus persicae</i> ) on kale		The crude extract was effective in controlling the green peach aphids. The order of the insecticidal activity of the four different concentrations was 75 > 50 > 25 > 10%.	[92]

Table 3. Cont.

Plant Name	Country of Origin	Plant Part Used	Focus of the Study	Treatment Application	Key Findings	Reference
<i>Solanum incanum</i>	Madagascar	Leaf powder	To control mustard rape aphids and tomato spider mites on tomatoes	Plant extracts from leaf powder at 12.5% <i>w/v</i> were mixed with 0.1% <i>v/v</i> soap. The treatments were applied 24 h post mixing the plant materials with water at a rate of one liter on an area of 5 m <sup>2</sup> using a knapsack sprayer fitted with a hollow cone spray nozzle.	Plant extracts from leaf powder at 12.5% <i>w/v</i> using 0.1% <i>v/v</i> soap can be used against rape aphids and tomato spider mites. <i>Solanum delagoense</i> (25%) reduced aphids and mites by 86.5% and 75%, respectively.	[90]
<i>Solanum incanum</i>	Madagascar	An aqueous crude fruit extract	To control ladybird beetle on <i>Brassica napus</i>	Concentration extracts at 5, 10, 15, 20 and 25% were applied by spraying <i>Brassica napus</i> plants under greenhouse conditions.	Concentration extracts at 25% caused the highest mortality of 80% on collected dead ladybird beetles.	[88]
<i>Tephrosia vogelii</i>	Zimbabwe	Leaf extracts	Control green bean aphids	Leaf extracts were made at three different concentrations (0.5%, 2% and 5% <i>w/v</i> ).	<i>T. vogelii</i> at 5% <i>w/v</i> reduced aphid infestation by 60%, while control reduced pest infestation by 27%. This resulted in 5% <i>T. vogelii</i> having yield of 1100 kg/ha compared to 190 kg/ha of the control.	[93]

**Table 4.** List of selected medicinal plant extracts used for antimicrobial (antifungal).

Plant Name	Country of Origin	Plant Part Used	Focus of the Study	Treatment Application	Key Findings	Reference
<i>Acorus calamus</i>	China	Root	Control banana fruit crown rot	Evaluation of plant extracts at various concentrations (1%, 5%, 10%, 25% and 50%) against <i>C. musae</i> was carried out by the ‘poisoned food technique’. The banana fruits were then dipped in plant extracts for 5 min and allowed to air dry for 6 h. Banana hands dipped in chemical benomyl (0.1%) served as positive control while distilled water was used as a negative control. One group was incubated at room temperature ( $28 \pm 2$ °C), and another group was held in low-temperature storage (14 °C and 90% RH) conditions.	Extracts of <i>A. calamus</i> (50%) significantly reduced crown-rot disease by up to 75% at room temperature (12 d of incubation) and up to 85% at cold storage (35 d of incubation) conditions.	[94]
<i>Allium cepa</i> × <i>Allium sativum</i>	Croatia	Leaves	Control banana fruit crown rot	Evaluation of plant extracts at various concentrations (1%, 5%, 10%, 25% and 50% concentration) against <i>C. musae</i> was carried out by the ‘poisoned food technique’. The banana fruits were then dipped in plant extracts (at 25% concentration) for 5 min and allowed to air dry for 6 h. Banana hands dipped in chemical benomyl (0.1%) served as positive control while distilled water was used as a negative control. One group was incubated at room temperature ( $28 \pm 2$ °C), and another group was held in low-temperature storage (14 °C and 90% RH) conditions.	The dipping of banana fruits in zimmu leaf extract at 25% concentration exhibited 100% inhibition of crown-rot disease in cold storage (14 °C) up to 35 d and increased the shelf life to 64 d. However, at room storage ( $28 \pm 2$ °C), the same treatment exhibited 86% inhibition of crown-rot disease up to 12 d.	[94]
<i>Aloe vera</i>	Oman	Leaves	Use of <i>Aloe vera</i> gel solution in controlling nectarine <i>Rhizopus stolonifer</i> , <i>Botrytis cinerea</i> and <i>Penicillium digitatum</i>	The fruits were treated by dipping with the corresponded <i>Aloe vera</i> gel solution for 10 min and allowed to dry at room temperature. After 24 h, the fruits were inoculated with <i>R. stolonifer</i> , <i>B. cinerea</i> or <i>P. digitatum</i> by depositing 20 µL the fungi stock (50 spores) inside the artificial injury made (2 × 2 × 2 mm of length, width and depth) on the nectarine cultivars and then stored in room temperature for 6 d.	<i>Aloe vera</i> (alone or with the addition of thymol) was effective in reducing fruit decay in the two nectarine cultivars by 50 and 70% depending on nectarine cultivar and fungus species.	[95]

Table 4. Cont.

Plant Name	Country of Origin	Plant Part Used	Focus of the Study	Treatment Application	Key Findings	Reference
<i>Aloe vera</i>	Oman	Leaves	Aloe vera gel edible coating in delaying rachis browning on grapes	The treatments were <i>Aloe vera</i> gel diluted 1:3 with distilled water, and distilled water served as control. The grapes were immersed in 5 min in respective treatments, air-dried before storage at 1 °C and 95% RH in permanent darkness for 35 d. Ten samples for both treated and control clusters were taken after 7, 14, 21, 28 and 35 d; half of them were immediately analyzed (cold storage), and the remainder were transferred to a chamber under controlled conditions at 20 °C and 90% RH and analyzed after 4 d to simulate market operations.	Results indicate severe symptoms of dehydration and browning in control rachises (plus SL scores > 3) and low effects for those clusters treated with <i>A. vera</i> gel (plus SL scores < 3) after 28 d of cold storage. After 35 days of storage, grapes treated with <i>Aloe vera</i> got plus SL score < 4, while the control got plus SL score > 5.	[96]
<i>Datura stramonium</i>	Mexico/Colombia	Leaves	Controlling soft-rot on mango fruits	<i>Datura stramonium</i> extracts were tested at 10%, 25% and 50% dilutions.	Control had higher mean soft-rot severity of 93.4%, while the <i>Datura stramonium</i> extracts at 25% reduced the severity of soft-rot by 41%.	[97]
<i>Galenia africana</i>	South Africa	Dried leaves	Effect of <i>Galenia africana</i> extracts alone and in combination with kresoxim-methyl for controlling <i>B. cinerea</i> on apples	The apple cultivar, Granny Smith, was wounded (5 mm in diameter and 3 mm in depth) three times halfway between the calyx and the stem end. A 20 µL drop of each plant extract and kresoxim-methyl was placed in the wounds and allowed to air-dry for 2 h before application of a 20 µL conidial suspension ( $1 \times 10^4$ spores mL <sup>-1</sup> ); the 20 µL drops had final plant extract doses of 0.0, 1.95, 3.91, 7.81, 15.63, 31.25 and 62.5 mg·mL <sup>-1</sup> , with or without kresoxim-methyl at 0.0 and 0.005 mg mL <sup>-1</sup> .	Kresoxim-methyl (2.5 mg·mL <sup>-1</sup> ) in combination with <i>G. africana</i> extract at doses of 125.0, 250.0 and 500.0 mg·mL <sup>-1</sup> showed high inhibition levels (73, 83.8 and 90.8%, respectively) compared to the kresoxim-methyl (72.5%). Inhibition of decay progression by 67.1% for the plant extract only (62.5 mg·mL <sup>-1</sup> ) was achieved compared to 37% of the control.	[98]

Table 4. Cont.

Plant Name	Country of Origin	Plant Part Used	Focus of the Study	Treatment Application	Key Findings	Reference
<i>Moringa olifera</i>	India	Leaf extracts	Effect of gum arabic (GA) coatings and moringa (M) leaf extract in controlling <i>Colletotrichum gloeosporioides</i> on 'Maluma' avocado fruit	Fruits were dipped into the treatments: GA 10%, GA 15%, GA 10% + M, GA 15% + M and CMC 1% + M, and the fruits were then stored at 5.5 °C (95% relative humidity (RH)) for 21 d and moved to ambient conditions at 21 ± 1 °C (60% RH) for 7 d to simulate a retail condition.	The study demonstrated that GA 15% + M (62.37 N) and CMC 1% + M (59.93 N) retained fruit firmness and lowered weight loss by 3.66% and 6.19%, respectively, and both suppressed mycelial growth of <i>C. gloeosporioides</i> on 'Maluma' avocado fruit by 33%.	[99]
<i>Phyllanthus niruri</i>	India	Leaves	<i>Phyllanthus niruri</i> as an edible coating to control postharvest anthracnose in dragon fruits	The fruits were inoculated by dipping for 2 min in a spore suspension of <i>C. gloeosporioides</i> ( $10^5$ spores mL <sup>-1</sup> ) with 0.1% (v/v) Tween 80 and air-dried at ambient (25 ± 2 °C). The fruits were then dipped for 2 min in 5.0 g L <sup>-1</sup> , 10.0 g L <sup>-1</sup> and 15.0 g L <sup>-1</sup> for <i>Phyllanthus niruri</i> crude extract and left to dry again at room temperature. Fruits dipped in spore suspension ( $10^5$ spores' mL <sup>-1</sup> ) with 0.1% (v/v) Tween 80 for 2 min served as control. All inoculated treated and untreated fruits were then packed in commercial packaging cartons and stored at 11 ± 2 °C, 80% RH for 28 d.	Phyllanthus niruri extracts at 5.0 g L <sup>-1</sup> or 10.0 g L <sup>-1</sup> significantly controlled anthracnose by 80 and 90%, respectively, after 28 d of cold storage at 11 ± 2 °C and 80% RH.	[100]
<i>Plumbago zeylanica</i>	Australia	Leaves	Control banana fruit crown rot	Evaluation of plant extracts at various concentrations (1%, 5%, 10%, 25% and 50% concentration) against <i>C. musae</i> was carried out by the 'poisoned food technique'. The banana fruits were then dipped in plant extracts (at 25% concentration) for 5 min and allowed to air dry for 6 h. Banana hands dipped in chemical benomyl (0.1%) served as positive control while distilled water was used as a negative control. One group was incubated at room temperature (28 ± 2 °C), and another group was held in low-temperature storage (14 °C and 90% RH) conditions.	Extracts of <i>P. zeylanica</i> (25%) recorded a significant reduction of crown-rot disease up to 75% at room temperature (12 d of incubation) and up to 85% at cold storage (35 d of incubation) conditions.	[94]

Table 4. Cont.

Plant Name	Country of Origin	Plant Part Used	Focus of the Study	Treatment Application	Key Findings	Reference
<i>Ruta chalepensis</i>	Egypt	Leaves	Controlling soft-rot on mango fruits	<i>Ruta chalepensis</i> extracts were tested at 10%, 25% and 50%.	Higher mean soft-rot severity was recorded on the untreated control 4.67 (93.4% fruit area affected); while the greatest reduction in the severity of soft-rot 1.33 (26%) was recorded in the extract of <i>Ruta chalepensis</i> at 50% concentration.	[97]
<i>Thymus vulgaris</i> L.	Italy	Leaves	The effect of edible coatings alone or in combination with thyme oil on anthracnose incidence and severity in inoculated avocado fruits	Evaluation of plant extracts at various concentrations was carried out by the ‘poisoned food technique’. The inoculated fruits were dipped in commercial treatment (prochloraz 0.05% for 5 min dip), chitosan (CH), aloe (AL), thyme oil (TO), CH+TO (3:1) and AL+TO (3:1), allowed to air dry at room temperature and stored for 5 d.	Coating with CH +TO and AL+TO combination was the most effective, and both combination treatments significantly reduced the percentage disease incidence by 80% and 75%, respectively.	[101]
<i>Zataria multiflora</i>	Iran	An essential oil from leaves	Preventing browning of button mushrooms ( <i>Agaricus bisporus</i> )	The treatments were control (water), TG (Tragacanth gum coating, 0.6%), TGZEO1 (0.6% TG + 1.0% 122 sorbitol + 100 ppm ZEO), TGZEO5 (0.6% TG + 1.0% sorbitol + 500 ppm ZEO), TGZEO10 (0.6% TG + 1.0% sorbitol + 1000 ppm ZEO) and SM (1000 ppm sodium metabisulphite). Mushrooms were dipped into their respective solutions for 5 min, and browning of button mushrooms was evaluated upon 16 d of storage at 4 °C.	Control and SM-treated samples had higher open cap mushrooms (82.2% and 80.0%, respectively). Over the same period, the percentage of open cap mushrooms coated with TGZEOs, TSs and TG were in the range 66.7–75.6%. After 16 days, the control had higher PPO and POD activity (75 and 25 units/mg protein, respectively) resulting in higher browning rate, while TG-coated mushrooms had lower browning rate in the range of 25–70 units/mg protein PPO and 15–20 units/mg protein POD.	[102]
<i>Zehmerria scabra</i>	Angola	Tubers	Control banana fruit crown rot	Evaluation of plant extracts at various concentrations (1%, 5%, 10%, 25% and 50% concentration) against <i>C. musae</i> by dipping the fruits in plant extracts (at 25% concentration) for 5 min and allowed to air dry for 6 h. Banana hands dipped in chemical benomyl (0.1%) served as positive control while distilled water was used as a negative control.	Extracts of <i>Z. scabra</i> (25%) and recorded significant reduction of crown-rot disease up to 75% at room temperature (12 d of incubation) and up to 85% at cold storage (35 d of incubation) conditions.	[94]

### 3.1. Medicinal Plant Extracts against Microbes in Horticultural Crops

Medicinal plants produce secondary metabolites with antimicrobial properties. Thus, their screening can provide an alternative for producing chemical fungicides that are relatively non-toxic and cost-effective [37,103]. Most of these compounds are terpenes with fungicide properties and can be used as phenolic compounds or essential oils to inhibit microorganisms [3,104]. Medicinal plant extracts can be directly used, or substances responsible for the antimicrobial properties can be isolated [105,106]. Although several studies on the antimicrobial effects of plant extracts have been performed, many medicinal plants used in different rural communities have never been evaluated for their antimicrobial effects [105,107].

Alemu et al. [97] investigated extracts from four plants (*Ruta chalepensis* (fringed rue), *Eucalyptus globulus* (eucalyptus), *Vernonia amygdalina* (bitter leaf) and *Datura stramonium* (jimsonweed)) at 10%, 25% and 50% dilutions in controlling soft-rot on mango fruits while in storage for 16 d at 25 °C (65 ± 5% RH). Higher mean soft-rot severity was recorded on the untreated control 4.67 (i.e., nearly 93.4% fruit area affected), while the most significant reduction in the severity of soft-rot 1.33 (26%) was recorded in the extract of fringed rue at 50% concentration. Extracts from jimsonweed at 25% and 50%, eucalyptus at 50% and bitter leaf at 25% dilution also reduced the soft-rot severity within a range of 2.07–2.40. In an in vivo study reported by Navarro et al. [95] on two nectarine cultivars ('Flavela' and 'Flanoba') dipped in *Aloe vera* gel alone or with the addition of thymol (99.5%) followed by inoculation with *R. stolonifer*, *B. cinerea* or *P. digitatum*, findings show that the application of aloe treatments (alone or with the addition of thymol) led to significantly lower fungus infection volume than in non-treated nectarines after incubation at 25 °C (85% RH) for 6 d. The results show that extracts of the different plant species are substantially varied in their antifungal potentials. According to Ogbebor and Adekunle [108], these differences are expected because plants vary in their chemical constituents, habitats and stages at which they were collected.

Bordoh et al. [100] applied extracts from *Zingiber officinale* (ginger), *Curcuma longa* (turmeric) and *Phyllanthus niruri* (gulf leaf-flower) as an edible coating to control postharvest anthracnose in dragon fruits after inoculating them with *C. gloeosporioides*. After storage in commercial packaging cartons at 11 ± 2 °C and 80% RH for 28 d, results show that gulf leaf-flower extracts at 10 g L<sup>-1</sup> significantly reduced the disease followed by turmeric extracts at 10 g L<sup>-1</sup> compared to control. On the other hand, dipping avocado fruits in chitosan + thyme oil (3:1) and aloe gel + thyme oil (3:1) significantly reduced the disease severity of *C. gloeosporioides* 80% and 75%, respectively, after storage at 20 °C and 70 ± 5% RH for 5 d [101]. The results also show that preventative dip treatment with chitosan or *Aloe vera* gel incorporated with thyme oil or stand-alone treatments showed lower incidence of anthracnose severity. According to Singh et al. [109], the antifungal activity of plant extracts against *C. gloeosporioides* could be due to the presence of bioactive compounds such as gingerols (in ginger), curcumin (turmeric), loin and aloe-emodin (aloe) and alkaloids in dukung anak.

In trying to reduce the severity of anthracnose on naturally infected berries, Cruze et al. [110] immersed the berries in extracts of neem (*Azadirachta indica*), orange (*Citrus sinensis*) extracts, essential oil emulsions of garlic (*Allium sativum*), diesel tree (*Copaifera langsdorfii*), cinnamon (*Cinnamomum zeylanicum*) and clove (*Eugenia caryophyllata*) extracts before storage at 24 ± 2 °C and RH of 85 ± 5% for 11 d. Results show that neem and citric extract at 4% was the most efficient treatment because the disease incidence was 19.44% and the disease severity was 9.34%, while the control showed disease severity of 75.13%. Less severity and, consequently, more disease control were also achieved by immersing the berries into the emulsion of essential oil of garlic, followed by treatments with diesel tree, clove and cinnamon (Table 3). According to Bautista-Baños et al. [111], compounds such as nimbin and quercetin present in the neem have fungicide activities, and thus they were more effective than the other medicinal extracts.

Sangeetha et al. [94] dipped banana fruits (cv. Robusta) in plant extracts of sweet flag (*Acorus calamus*), haritaki (*Terminalia chebula*), dawidjies (*Zehneria scabra*), doctorbush (*Plumbago zeylanica*), shallot (*Allium cepa* × *Allium sativum*), mamijava (*Enicostemma littorale*), orange climber (*Toddalia asiatica*) and arni (*Clerodendron phlomoides*) at 25% concentration to control crown-rot of banana. After storage for 12 d at room temperature ( $28 \pm 2$  °C and 80% RH) and 35 d at low-temperature storage (14 °C and 90% RH), results show that dipping of banana fruits in aqueous leaf extract of shallot significantly reduced the crown-rot disease by 86% compared to control and other treatments (Table 4). Gosh et al. [112] reported that the antimicrobial compounds are abundantly present in medicinal plants, and these might be involved in the defence of plants against microbial pathogens in addition to their direct antimicrobial activity against crown-rot disease in bananas.

### 3.2. Medicinal Plant Extracts against Pests in Horticultural Crops

About 50% of total crops are lost annually because of insect and pest attacks, which adversely affect world food production and huge economic losses [12,39,113,114]. The use of pesticides has contributed immensely to the increase in agricultural productivity; however, these pesticides lead to serious environmental pollution, affecting human health and causing the death of non-target organisms [115]. There is now an increasing trend in the use of botanicals with more than 2400 bioactive medicinal plant species identified for their pesticide and antipathogenic properties [40,116].

According to Isman and Grieneisen [117], scientists continuously search for novel pest control products from medicinal plants. The rich flora found around the world provides known medicinal plant species that may exert insecticidal properties based on their chemistry and efficacy under laboratory conditions [118,119]. Using medicinal plant extracts for pest control has several advantages in terms of preventing the development of insecticide resistance due to the usual presence of several bioactive compounds, their low persistence in the environment and their generally low cost, particularly for smallholder farmers with limited income [120–122].

Muzemu et al. [90] reported that fever tea (*Lippia javanica*) leaf powder extract at 12.5% w/v using 0.1% v/v soap could be used against rape aphids and tomato spider mites. Extracts of fever tea leaf powder and bitter apple (*Solanum delagoense*) ripe fruit pulp were evaluated as alternatives to conventional pesticides against rape aphids and tomato red spider mites under on-station conditions. The fever tea and bitter apple applied at 12.5% and 25% reduced aphids by 83% and 75.9% and mites by 86.5% and 75%, respectively. Both extracts were more effective against aphids than mites while fever tea was more effective than bitter apple on both crop pests. According to Manenzhe et al. [123], the reduced number of aphids and mites could be due to extracts' repellent, toxic and anti-feedant effects since they contain essential oils and alkaloid constituents with pesticide properties. This shows that fever tea and bitter apple had some insecticidal effects against the vegetable pests (Table 3).

Mazhawidza et al. [88] did a trial on direct topical and residual sprays of aqueous extracts of jimsonweed (*Datura stramonium*), snake bean plant (*Bobgunnia madagascariensis*) and bitter apple against the ladybird beetle on rape (*Brassica napus*). The crude extracts of jimsonweed fresh leaves, bitter apple fresh fruits and snake bean plant dried pods were applied separately at 5, 10, 15, 20 and 25% w/v under laboratory conditions. Mortality of ladybird beetle in laboratory bioassays increased with an increase in post-exposure time, and snake bean plant (25% w/v) caused the highest mortality. Based on lethal dose at 50% (LD<sub>50</sub>) values, snake bean plant extracts were most toxic (LD<sub>50</sub>, 30% w/v) followed by jimsonweed (LD<sub>50</sub>, 34% w/v) and bitter apple (LD<sub>50</sub>, 49% w/v) 24 h post-application. Under laboratory conditions, significantly higher ladybird beetle mortality rates from snake bean plant than *D. jimsonweed* and bitter apple were observed [124]. This observation may have been due to saponins in snake bean plant and other anti-feedant compounds such as quercetin. The results show that jimsonweed and bitter apple extracts at the application rates used in the study were relatively safer to *H. variegata* than snake bean plant (25%

*w/v*). These ladybird beetles have been reported in horticultural crops such as spinach, tomatoes, cabbage, radish, etc. [125]. Hence, jimsonweed and bitter apple can be explored for integrated pest management programs of horticultural crops (Table 3).

Kayange et al. [93] evaluated the effectiveness of fish bean (*Tephrosia vogelii*) and candida (*Tephrosia candida*) extracts against green bean aphid (*Aphis fabae*) at three different dilutions (0.5%, 2% and 5% *w/v*). According to the authors, there was a high mortality rate of aphid on the plots treated with fish bean compared to plots treated with candida at the same dilution. These plant extracts at 5% significantly controlled the green bean aphid. According to Stevenson and Belmain [98], the presence of isoflavonoids which are toxic substances in fish bean might have reduced the presence and population of aphids. The active components in leaves of fish bean have anti-feedant, insecticidal, acaricidal, ovicidal and ichthyotoxic effects, which act as a stomach poison in insects [126].

Sharma and Gupta [87] evaluated the biological activity of plant extracts against cabbage moth (*Pieris brassicae*) (Linn.) on cabbages. Aqueous extracts (10, 5, 2.5 and 1.0%) from leaves of neem (*Azadirachta indica*), chinaberry tree (*Melia azedarach*), wild-sage (*Lantana camara*), hemp (*Cannabis sativa*), oleander (*Nerium indicum*), *Eucalyptus* sp., castor bean (*Ricinus communis*) and black nightshade (*Solanum nigrum*) were used as treatments. The protection of cabbage foliage at all the dilutions of *M. azedarach* was higher when compared to other plant extracts. The maximum protection was provided at 5% of chinaberry tree (88.3%) and neem (82.5%). The minimum (4.6%) protection to the cabbage foliage was observed at 1% of neem. The anti-feedant effect of the different concentrations decreased with a decrease in concentration. Irrespective of plant extract, high doses resulted in maximum mean protection to foliage (68.1%), while the lowest dose, 9.5%, resulted in the least protection (Table 3).

#### 4. Medicinal Plant Extracts Preserve Quality Attributes of Horticultural Crops

Fruits and vegetables are highly perishable, and during the postharvest period, there are considerable losses due to several physicochemical changes that occur during storage. Biochemical deterioration, such as browning, off-flavour and texture breakdown, decreases the quality and value of horticultural crops, thereby risking market acceptability [8,10,84]. The antioxidative properties of medicinal plant composition can be essential in preserving quality attributes, delaying senescence and maintaining quality attributes of crops [84,97].

##### 4.1. Effect of Medicinal Plant Extracts on Physiological Attributes of Horticultural Crops

Ahmed et al. [127] applied an aqueous *Aloe vera* gel (AVG) solution on nectarine fruits stored at  $0 \pm 0.5$  °C and  $90 \pm 5\%$  RH for 6 weeks. Results show that control fruits exhibited a significant increase in ethylene production ( $6 \mu\text{mol kg}^{-1} \text{h}^{-1}$ ), while fruits coated with *Aloe vera* gel ( $2 \mu\text{mol kg}^{-1} \text{h}^{-1}$ ) did not show any significant change in ethylene production up to 6 d of fruit ripening. The control fruit respiration rate increased more rapidly ( $70 \text{ mmol CO}_2 \text{ kg}^{-1} \text{h}^{-1}$ ), and on 8 d of fruit ripening, these fruits exhibited a 41% higher respiration rate compared to fruit coated with the *Aloe vera* gel ( $28.7 \text{ mmol CO}_2 \text{ kg}^{-1} \text{h}^{-1}$ ). At the fully ripe stage, AVG-coated fruit showed a 65% reduction in moisture loss than the control. The interaction between treatment and ripening time for fruit moisture loss was significant. On the other hand, Nourozi and Sayyari [128] revealed that dipping apricots in a combination of *Aloe vera* gel (AVG) and basil seed mucilage (BSM) resulted in the reduction in ethylene at the end of 28 d in cold storage (2 °C and 85–90% RH). At the end of the experiment, fruits coated with AVG alone showed a low respiration rate compared to other treatments (Table 4). According to Akbudak and Eris [129], the physiological attributes were maintained because the AVG coating may be ascribed to a modified atmosphere around the fruit that potentially reduces the ethylene sensitivity and production.

Based on the study by Ozturk et al. [130], immersing cherry laurel fruits (*Prunus laurocerasus* L.) in AVG and modified atmosphere packaging (MAP) helped in maintaining the physiology of the fruits after cold storage ( $\pm 0.5$  °C and  $90 \pm 5\%$  RH) for 60 d. The

highest weight loss was in the control treatment (6.04%) at the end of storage, the weight loss in single MAP treatments was 0.92% at the end of storage, and single AVG treatments had a weight loss of (0.52%) at the end of storage. Except for AVG treatments, there was an increase in respiration rates of the other treatments on the 15 d of storage, but decreases were observed through the rest of storage, especially on the 30 d of storage. The highest ethylene production in this period was measured in control treatment ( $0.20 \mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1}$ ), and it was respectively followed by MAP ( $0.18 \mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1}$ ), AV+MAP ( $0.15 \mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1}$ ) and AV ( $0.12 \mu\text{L C}_2\text{H}_4 \text{ kg}^{-1} \text{ h}^{-1}$ ) treatments. At the end of storage, the highest decay rate (19.90%) was observed in control, and the lowest decay rate (1.89%) was observed in AV+MAP treatments (Table 4). Khan and Singh [131] and Erkan and Eski [132] reported that AVG+MAP induced atmospheric conditions (high  $\text{CO}_2$  and low  $\text{O}_2$ ) and significantly reduced respiration rate and ethylene synthesis of the cherries.

Anjum et al. [133] observed that dipping guava fruits in extracts of ginger (*Zingiber officinale*), garlic (*Allium sativum*) and aloe (*Aloe vera*) mixed with edible coating significantly reduced moisture loss after storage at  $25 \pm 3 \text{ }^\circ\text{C}$  (65% RH) for 15 d. Loss in weight was higher in control (28%) compared with guava fruits coated with ginger extract + gum arabic (22.36%), *A. sativum* + gum arabic (20.65%) and aloe coating + gum arabic (21.76%) (Table 4). Findings by Chauhan et al. [134] reveal that among the neem-based formulations used to control weight loss of 'Starking Delicious' apple (*Malus domestica* Auyh), nimbecidine (1.5%) was found better in reducing physiological weight loss after refrigerated storage ( $1 \pm 1 \text{ }^\circ\text{C}$ ) for up to 180 d. On the other hand, the same fruits treated with 20% drake leaf extract proved to be the most effective treatment in reducing weight loss. Wijewardane and Guleria [135] reported that the application of extracts from *Azadirachta indica* (neem oil) and marigold flower (*Tagetes erectus*) along with cold storage ( $2 \pm 1 \text{ }^\circ\text{C}$  and 85–90% RH) for 150 d helped in maintaining the physiology of apple (*Malus domestica*) cv. Royal Delicious in 2006 and 2007. The results reveal that coating of fruits with 2% neem oil with shrink-wrapped tray packing had the minimum physiological weight loss of 3.4% in 2006. However, in 2007, the lowest physiological weight loss (3.5%) was recorded from the treatment with pre-cooling followed by fruits coated with 1.5% neem oil (Table 4). According to Baswa et al. [136], reduction in weight loss with the use of neem leaf extract may be attributed to the presence of principle compound azadiractin which can form a film around the fruits and reduce moisture loss under low-temperature conditions as compared to ambient condition; thus the neem leaf extract was more efficient at cold storage compared to ambient temperature. The fruits treated with medicinal extract created a modified atmosphere that slowed the metabolic rate around the fruits; thus, the decay rate and shelf life were improved compared to the control under the same storage conditions. Loss of moisture increased due to desiccation and increased metabolic activities such as respiration rate [137].

Strawberry fruits (*Fragaria* × *ananassa* Duch. cv. Sabrina) dipped in lemon verbena (*Aloysia citrodora*) bio-extract and stored at  $4 \text{ }^\circ\text{C}$  (90–95% RH) for 12 d responded positively to medicinal plant treatments against weight loss. Moshari-Nasirkandi et al. [138] reported that the different concentrations of lemon verbena extracts influenced the storage period of strawberry fruits. Control fruits dipped in distilled water had the highest weight loss while the lowest weight loss was obtained in fruits treated with  $600 \text{ mg L}^{-1}$  lemon verbena extract. Alemu et al. [97] reported that the weight loss in mango fruits can be controlled by using an aqueous extract from jimsonweed, eucalyptus and fringed rue (*Ruta chalepensis*) at 50% after storage for 16 d at  $25 \text{ }^\circ\text{C}$  ( $65 \pm 5\%$  RH). The authors reported that the weight loss was controlled, and the marketability of mango fruits was maintained in a range of 72–87%, with no significant difference among them (Table 4). Medicinal plant extracts can check the moisture loss by creating a modified atmosphere around the fruits, thus reducing weight loss [111].

#### 4.2. Effect of Medicinal Plant Extracts on Fruit Physical Attributes

After cold storage ( $1 \pm 1$  °C and 90% RH) for 180 d, coated 'Starking Delicious' apple (*Malus domestica* cv. Auyh) retained higher firmness when treated with 20% neem leaf extracts [134]. Among neem-based formulations applied, nimbecidine (1.5%) had the most noteworthy effect in retaining fruit firmness. Dipping apple (*Malus domestica* cv. Royal Delicious) in 2% neem oil coupled with shrink-wrapped tray packing and cold storage ( $2 \pm 1$  °C and 85–90% RH) for 150 d resulted in higher firmness in the years 2006 and 2007 [118]. Moreover, 2% neem oil coupled with shrink-wrapped tray packing was the most effective treatment in retaining fruit firmness (67.3 N) and (66.4 N) in 2006 and 2007, respectively (Table 4). Based on the study by Alemu et al. [97], dipping mango fruits in fringed rue (50%) and storage for 16 d at 25 °C ( $65 \pm 5\%$  RH) resulted in the highest firmness (9 N), which was greater than carbendazim fungicide (8.93). This was followed by eucalyptus and jimsonweed at 50% and extract from bitter leaf (*Vernonia amygdalina*) at 25% dilution with values of 8.20 N, 8.13 N and 7.93 N, respectively, and they were effective in maintaining the firmness of mango compared to the control. The possibility of achieving a modified atmosphere condition through the coatings might have led to reduced metabolic rates and prevention of water loss, thus maintaining the fruit firmness.

Navarro et al. [95] reported that dipping nectarine cultivars ('Flavela' and 'Flanoba') in *Aloe vera* gel alone resulted in 30% higher firmness values than non-treated ones after 6 d of storage at 25 °C (85% RH). Control fruits showed decreased fruit firmness during storage from their initial values, with percentages of firmness losses of about 80% from their initial value. Immersing nectarine fruits in an aqueous solution containing *Aloe vera* gel and cold storage ( $0 \pm 0.5$  °C and  $90 \pm 5\%$  RH) for six weeks resulted in higher firmness than the control [127]. At the fully ripe stage, fruit coated with *Aloe vera* gel exhibited 40% more firmness than the control fruits, and the interaction between treatment and ripening time for fruit firmness was found to be significant. Abbasi et al. [139] reported that the highest firmness indicates a low level of anthracnose infestation, as fruit firmness and disease severity are negatively correlated.

In trying to maintain avocado fruit firmness, Bill et al. [101] reported that dipping the fruits in thyme oil + chitosan and storage at 20 °C ( $70 \pm 5\%$  RH) for 5 d had significantly higher fruit firmness (18.1 N) compared to prochloraz fungicide (15.1 N) treatments and control (10.3 N). Uncoated control fruit showed a lower hue angle value indicating loss of the original green colour, while fruits coated with thyme oil + chitosan and *Aloe vera* gel + thyme oil had a higher hue angle, but it was not significantly different to prochloraz fungicide (Table 4). A study by Ozturk et al. [130] showed that cherry laurel fruits (*Prunus laurocerasus* L.) immersed in 33% AVG and modified atmosphere packaging (MAP) had higher flesh firmness (2.3 N) on 60 d of storage at  $0 \pm 0.5$  °C ( $90 \pm 5\%$  RH). Compared to the control, the other treatments did not yield significant changes in lightness ( $L^*$ ) values. In all measurement dates throughout the storage, the lowest chroma value was obtained from the control treatment. While AVG and control treatments had similar hue angles throughout the storage, MAP-treated fruit had lower hue angles than the control. According to Chafer et al. [140], hue angles indicating red colour development were lower in MAP and AV + MAP treatments than in control treatment, and such findings indicated that present treatments induced red colour development. The maintenance of fruit firmness with the plant extracts could be related to lower weight loss and delayed ripening, shown by the delayed pulp colour (yellow, higher hue angle) development [10,140,141].

Gulhane et al. [142] reported that after storage at 14 °C (55% RH) for 45 d, skin colour analysis showed that apples were found to be excellent while tomatoes and apples were good, papaya and chikoo were slightly dull, and banana was <50% brownish in colour after treatment with 10% *Aloe vera* gel and 20% marigold flower extract (Table 4). Pulp colour analysis showed that apple and tomato were 100% good, papaya 75% good, chikoo 50% good and banana 25% good. This could be attributed to the delayed ripening process caused by the treated fruits that can create a semi-permeability atmosphere created by

coatings on the surface of the fruits which might have modified the internal atmosphere by controlling O<sub>2</sub> and CO<sub>2</sub> concentrations in the fruit [140].

#### 4.3. Effect of Medicinal Plant Extracts on Chemical Attributes

Findings by Moshari-Nasirkandi et al. [138] indicate that the storage period and various concentrations of lemon verbena extract had significant effects on the TSS of strawberry fruits stored at 4 °C (90–95% RH) for 12 d. The highest TSS of strawberry fruit was observed in E600 mg L<sup>-1</sup> and after 8 and 12 d of storage, and the lowest TSS occurred in control on the 4th and 8 d of storage. During the 12 d of storage, the TSS of strawberry fruit increased from 2.60 to 5.00. Ahmed et al. [127] reported that immersing nectarine fruits in *Aloe vera* gel and cold storage (0 ± 0.5 °C and 90 ± 5% RH) for 42 d resulted in the fruit coated with *Aloe vera* gel exhibiting a significantly lower TSS of 14° Brix and TSS: TA ratio (1:20), while the control had TSS of 18° Brix and TSS: TA (1:40). Alemu et al. [97] reported that storing mango fruits at 25 °C (65 ± 5% RH) for 16 d after dipping them in wild-sage extract (10 and 25%) and bitter leaf (10%) resulted in a high TSS value (17.2, 17.47 and 17.93° Brix, respectively). According to Kittur et al [143], the change in chemical attributes such as TSS could be due to hydrolytic changes in starch and conversion of starch to sugar which is an important index of the ripening process in mango and other climacteric fruit.

El-Eryan et al. [144] reported that the control recorded higher total acidity (TA) (0.147%) after 28 d of cold storage, and it reached about 0.143% during marketing, while the neem extract at 10% had higher vitamin C (131.83 mg/100 ml) during the cold storage period, and it was 137.16 mg/100 ml 6 d of marketing. Results by Wijewardane and Guleria [135] reveal that 1.5% and 2% neem oil treatment retained the higher TA content (0.3%) with the minimum fruit juice pH (3.7) in 2006, whereas 1.5% neem oil recorded the lowest value of pH (3.6) in the year 2007 for pre-cooled fruits packed in a shrink-wrapped tray package after cold storage (2 ± 1 °C and 85–90% RH) for 150 d. The lower level of titratable acidity content and higher pH were recorded in the control treatment. Ozturk et al. [130] revealed that when compared to the control (9.7 g kg<sup>-1</sup>), the treatments had higher titratable acidity only on the 15 d of storage with modified atmosphere packaging obtaining 12.0 g kg<sup>-1</sup>, *Aloe vera* obtaining 11.7 g kg<sup>-1</sup> and *Aloe vera* +MAP obtaining 12.0 g kg<sup>-1</sup> (Table 4). Findings by Moshari-Nasirkandi et al. [138] indicate that the highest and lowest TA of fruits was obtained in control and E600 mg L<sup>-1</sup>, respectively. Results show that the pH was in its highest amount in E600 mg L<sup>-1</sup> and on 4 d and 12 d of storage, whereas the lowest amount was obtained in control fruit. On the 12 d of storage, the pH of strawberry fruit increased from 3.74 to 4.07. According to Shin et al. [145], this might be due to the breakdown of organic matter to sugars and their involvement in the respiration cycle. Coated fruit exhibited a reduction of organic acid loss due to the low oxygen permeability and lowered respiration rate and consequent prevention of acid oxidation [146].

Ahmed et al. [127] reported that TA (29%) was significantly higher in AVG (0.8%) than uncoated nectarine fruit (0.45%) at the ripe stage. The interaction between treatment and ripening time for TSS and TSS:TA was found to be significant. Control fruit showed a higher TSS:TA ratio than treated fruits because of a lower acidity due to oxidation and a higher TSS level than the coated fruit. Alemu et al. [97] reported that the lowest TA was recorded in 10% bitter leaf and 25% basil (*Ocimum basillicum*) with a value of 0.49. While fruit treated with the aqueous extract of jimsonweed and bitter leaf at 50% and eucalyptus, rosemary (*Rosmarinus officinalis*) and fringed rue at both 25% and 50% concentration exhibited relatively significantly higher TA contents. The highest pH was recorded in control (5.14), and fruit treated with wild-sage extract at all concentrations, malabar nut (*Adatoda schimperiana*), jimsonweed and bitter leaf at 10% and basil at 25% ranged from 4.86 to 5.10 with no significant difference among them. The lowest pH was recorded in fruits treated with 50% aqueous extract of malabar nut, jimsonweed, eucalyptus, rosemary, fringed rue and bitter leaf and the synthetic fungicide, all of which did not vary significantly (Table 4). Sha et al. [147] reported that enzymatic activity during storage is

another reason for decreasing fruit acids. The faster rate of decline of acidity in fruits in the control treatment could be due to the faster metabolic reactions occurring within them; thus, applying different coating treatments may also slow down the metabolism of fruits.

Anjum et al. [133] reported that after storage at  $25 \pm 3$  °C and 65% RH, among the different combinational treatments, garlic extract + gum arabic (14.66%) substantially inhibited the increase of TSS concentration after 15 d of storage compared with control (15.33%), while the reducing sugar concentration was significantly lower in guava fruits coated with garlic extract + gum arabic (1.88%) compared with control (2.45%). The concentration of non-reducing sugars was significantly higher in controls (1.32%) on day 3; however, after 15 d of storage, non-reducing sugars were higher in guava fruits coated with *Aloe vera* gel + gum arabic (2.52%). The lowest pH was found in control (3.85) and the highest was noted in fruits coated with *Aloe vera* + gum arabic (4.07). The highest TA concentration was found in garlic extract + gum arabic combination (1.12%) compared with control (0.95%). Coating treatments inhibit ripening, subsequent senescence and conversion of starch into sugar contents [148,149].

#### 4.4. Effect of Medicinal Plant Extracts on Phytochemical Content and Antioxidant Capacity

Rahmanzadeh-Ishkeh et al. [150] reported that dipping raspberry fruits in lemon verbena essential oil (EO) and cold storage ( $4 \pm 1$  °C and 90–95% RH) for 9 d improved the total flavonoid content (TFV) of fruits treated with  $750 \mu\text{L}^{-1}$  EO, and the lowest amount was observed in control fruits. Findings by Moshari-Nasirkandi et al. [138] reveal that dipping strawberry fruits (*Fragaria × ananassa* Duch. cv. Sabrina) in lemon verbena bio-extract at  $600 \text{ mg L}^{-1}$  increased their total flavonoid content (TFC) and total phenolic content (TPC), and the lowest was found in control fruit during the storage at 4 °C with 90–95% RH for 12 d. Ozturk et al. [130] reported that the TPC and TFC decreased after immersing cherry laurel (*Prunus laurocerasus* L.) fruits into 33% AVG, storing them at  $21 \pm 1$  °C ( $80 \pm 5\%$  RH). However, compared to the control, treated fruits had higher TPC and TFC. On the other hand, findings by Anjum et al. [133] reveal that the TFC in guava was significantly increased in guava fruits coated with garlic extract (20%) + gum arabic (10%) treatment ( $10.52 \text{ g kg}^{-1}$ ) than control ( $4.52 \text{ g kg}^{-1}$ ) after 15 d of storage at room temperature ( $25 \pm 3$  °C and 65% RH). Guan and Dou [151] reported that plant extract treatments can inhibit ethylene synthesis and delay TFC, TPC compound and anthocyanin accumulation, thus delaying the degradation of these compounds. The plant extract treatments were more effective in maintaining the bioactive compounds by creating a modified atmosphere around the fruits, thus the higher TPC and TFC values compared to the control.

Ahmed et al. [127] reported that immersing nectarine fruits in an aqueous solution of *Aloe vera* gel and cold storage ( $0 \pm 0.5$  °C and  $90 \pm 5\%$  RH) for 42 d maintained the total antioxidants at a lower level ( $215 \text{ mM Trolox } 100 \text{ g}^{-1} \text{ FW}$ ), compared to the uncoated fruit ( $270 \text{ mM Trolox } 100 \text{ g}^{-1} \text{ FW}$ ). The mean level of total antioxidants in ripe fruit coated with AVG remained 13% lower than in the control fruit. In AVG-coated fruit pulp tissues, the reduction in the level of total antioxidants may be due to increased activity of cytochrome oxidase, ascorbic acid oxidase and peroxidase enzymes [152]. Rahmanzadeh-Ishkeh et al. [150] reported that the highest antioxidant activity was observed in the fruits treated with  $750 \mu\text{L}^{-1}$  EO within the third day with  $134.50 \text{ mmol Fe}^{2+} \text{ L}^{-1}$  of the fruit juice. On the other hand, the least amount of antioxidant activity was identified in the control fruits on the sixth day with  $82.36 \text{ mmol Fe}^{2+} \text{ L}^{-1}$  of juice. According to Asghari and Agdam [153], the phenolic compounds of EOs of lemon verbena have antifungal properties and play a key role in the resistance of plants against attacks of a pathogen, and thus the various components of the EOs were effective and useful in controlling microbial growth by enhancing the antioxidant capacity in berry fruits. A report by Ozturk et al. [130] indicated that the antioxidant activity in all periods of the storage, AVG+MAP-treated fruit had higher total antioxidants (both ABTS and FRAP assay) than both the control and fruit treated with MAP and AVG. However, antioxidant activity (in ABTS and FRAP assay) decreased throughout the storage period. A report by Anjum et al. [133] revealed that

the highest total antioxidants were noted in AVG + gum arabic combination (814.6 mmol kg<sup>-1</sup>), but it was lower than the control (821.6 mmol kg<sup>-1</sup>). Overall, fruits treated with ginger extract + gum arabic exhibited the lowest total antioxidants than others. According to Maqbool et al. [154], the presence of different bioactive compounds such as ascorbic acid, phenolic and flavonoids contributes to the antioxidant activity of fruits, and degradation of these bioactive compounds leads to the reduction of antioxidant activity. Khaliq et al. [155] reported that coatings such as gum arabic or AVG restrict O<sub>2</sub> availability and reduce the extent of oxidation, and the medicinal extracts might have acted synergistically and further reduced its oxidation.

A report by Moshari-Nasirkandi et al. [138] revealed that the highest ascorbic acid was recorded on strawberry fruits treated with E600 mg L<sup>-1</sup> (134.2 mg 100 g<sup>-1</sup> FW) and the lowest ascorbic acid value was recorded for control (89.65 mg 100 g<sup>-1</sup> FW). During the 12 d of storage, the PAL and GPX enzyme activity in strawberry fruit increased from 0.386 to 0.538 U/mL and from 0.017 to 0.03 μmol/min/g FW, respectively. The highest PAL enzyme activity (0.614 U U/mL) and GPX enzyme activity (0.032 μmol/min/g FW) were obtained in E600 mg L<sup>-1</sup> and after the 4 d storage, whereas the lowest PAL and GPX enzyme activity was found in control fruit. According to Jiang et al. [156] and Zhang et al. [157], lemon verbena bio-extract prevented the activity of PPO and POD enzymes, which decompose the anthocyanins in litchi fruits. Grobelna et al. [158] reported that lemon verbena induced ROS scavenging systems that act as antioxidative and anti-senescence agents and improve shelf life, enhancing the postharvest quality and antioxidant capacity of fruits. Ahmed et al. [127] indicated that the control fruits showed a rapid rise in the level of ascorbic acid and exhibited a 13% higher ascorbic acid level compared to the coated fruit 42 d after storage. Control fruit showed a 16% higher mean level of ascorbic acid than AVG-coated fruit during ripening after cold storage. The reduction in ascorbic acid in coated fruit could be ascribed to the higher ascorbate oxidase activity reported by Yahia et al. [159] in tomato and bell pepper.

#### 4.5. Effect of Medicinal Plant Extracts against Postharvest Physiological Disorders

In trying to control chilling injury (CI) in cold storage (10 ± 1 °C and 90% RH) for 28 d, Etemadipoor et al. [160] immersed guava fruits in solutions of gum arabic (10%), oleic acid (1%) and cinnamon essential oil (1%) either solely or in combination with each other. The combination of gum arabic, oleic acid and CEO could be a useful edible coating for preventing chilling injury as it significantly delayed the development of browning on guava. Rasouli et al. [161] applied salicylic acid (SA) and AVG edible coating in CI on orange fruits. The oranges were submerged for 5 min in distilled water (DW), 2 mM SA, 30% AV and 2 mM SA + 30% AVG and stored at 4 ± 1 °C (80 ± 5% RH) for 80 d. CI symptoms were first detected after 60 d of storage in control, SA and AVG treatments, while in SA + AVG coating, it was first observed at 80 d of storage. The CI symptoms in control were higher than all treatments at 80 d of storage, while there were no significant differences among treatments. Results show that the application of cinnamon oil and gum arabic and SA and AVG solely or their combination could alleviate chilling disorder by increasing antioxidant systems and maintaining the integrity of cell walls.

Anjum et al. [133] reported that skin browning was significantly less in guava fruits treated with gum arabic + garlic extract from 3 to 15 d, compared with control. After 15 d, there was significantly less skin browning (all fruits had 21–40% browning) in garlic extract + gum arabic combination compared with control (33.33% fruits had 61–80% browning, and 66.66% fruits exhibited 81–100% browning). Overall, gum arabic (10%) + ginger extract (20%) and gum arabic (10%) + AVG (100%) coating treatments were effective in suppressing skin browning and significantly better than the control. Ali et al. [162] reported that the coating treatment inhibited oxidation of phenols and delayed browning, and thus skin browning was found lowest in guava fruits treated with gum arabic + plant extracts, probably owing to reduced phenolic oxidation. Films and coatings contain antioxidant agents that prevent enzymatic browning and therefore lessen the rate at which phenolic

compounds are converted to brown pigments [163,164]. Valverde et al. [96] immersed grapes in AVG edible coating in delaying rachis browning in storage of 1 °C (95% RH) in permanent darkness for 35 d. Ten samples for both treated and control clusters were taken after 7, 14, 21, 28 and 35 d; half of them were immediately analysed (cold storage), and the remainder were transferred to a chamber under controlled conditions at 20 °C (90% RH) and analysed after 4 d to simulate market operations. Panellists evaluated the visual aspect of the rachis and gave the highest scores to those rachises of control clusters, which became significantly different from 7 d of cold storage compared to treated clusters. These results indicate severe symptoms of dehydration and browning in control rachises after 7 d at 1 °C plus SL (scores > 3) and slight, moderate effects for those clusters treated with AVG after 28 d of cold storage. These results reveal that AVG coating could be used in delaying rachis browning on table grapes. Carvajal-Millan [165] reported that AVG coating controlled polyphenol oxidase activity responsible for causing rachis browning on table grapes.

In controlling browning of button mushrooms (*Agaricus bisporus*) stored for 16 d at 4 °C (90% RH), Nasiri et al. [102] dipped mushrooms in control (water), TG (Tragacanth gum coating, 0.6%), TGZEO1 (0.6% TG + 1.0% 122 sorbitol + 100 ppm *Zataria multiflora* essential oil (ZEO)), TGZEO5 (0.6% TG + 1.0% sorbitol + 500 ppm ZEO), TGZEO10 (0.6% TG + 1.0% sorbitol + 1000 ppm ZEO) and SM (1000 ppm sodium metabisulphite). Mushroom gills colour, dark zones, off-odour, gill uniformity and cap uniformity significantly changed with storage time, supporting the validity of using these parameters as indicators of mushroom deterioration. Promoting off-odour was noticeable in the control sample after 8 d of storage. The colour of the mushroom gradually became browner during the storage of all treatments. Based on judgments made by a sensory panel of 395 members, the best manner to defer dark spots formation and uniformity conversion of the cap surface was by applying TGZEO5 coating. Although there were no significant analytical differences between TGZEOs and TG, the results demonstrate that TGZEO5 treatment was more effective in postponing mushroom sensory decadence. TGZEO1 coating caused a diminution of spoilage organisms, such as pseudomonas, undertaking oxidation of phenolic compounds to form brown-coloured melanins; it prevents the formation of brown stains, therefore amending the appearance and colour and sensory decadence.

## 5. Modes of Action of Medicinal Plant Extracts in the Protection and Preservation of Horticultural Crops

The rare occurrence of infectious diseases in medicinal plants serves as a fundamental indication of the presence of competent defence mechanisms [166]. Due to difficulty in studying the complex interaction between the pathogen, antagonist, host and other micro-organisms present on the fruit surface, few attempts have been made to study the microbial interactions in fruit surface and wounds [60,167]. Knowledge of the mechanism of action is a key factor in achieving efficient inhibition of pathogens in their hosts [167,168]. Understanding the mechanism by which the biocontrol of fruit diseases occurs is critical to the eventual improvement and wider use of medicinal plant extracts to control diseases [60]. Mechanisms such as nutrient and space competition, induced resistance, antibiosis and parasitism operate alone or in concert with others and are involved in antagonistic interactions in the fructoplane [167,168]. A good understanding of the relationships between pathogens, antagonistic micro-organisms, fruit and the environment is essential for successfully implementing medicinal plant extract control in the postharvest phase [60,168].

According to Meskin et al. [169], different mechanisms of action through which phytochemicals can exert antimicrobial activities include (i) inhibition of the activity of enzymes and toxins; (ii) damage of the bacterial membrane; (iii) suppression of virulence factors; (iv) formation of biofilm; (v) inhibition of protein synthesis; and (vi) quorum quenching. For example, the mode of action of tannins is based on their ability to bind proteins, thereby inhibiting cell protein synthesis [46,48], while phenolic compounds are known to alter membrane functionality of pathogens; however, more investigations on the

mode of action of such plant products are required before their recommendation for the control of horticultural crops postharvest diseases [170].

The presence of many bioactive chemicals in medicinal plant extracts is most likely that their antimicrobial activity is not attributable to one specific mechanism but to diverse modes of action [60,171]. The authors reported that EOs derived from medicinal plants play a role in plant defence mechanisms against phytopathogenic micro-organisms, and the synergism between their different components reduces the development of resistant races of fungi. For example, winter cherry (*Withania somnifera*) and shittah tree (*Acacia seyal*) extract controlled green mold by a stimulatory effect on host defence mechanisms [170,172]. Mekbib et al. [172] reported that these defence mechanisms resulted in the synthesis of the cell wall that could serve as a physical and biological barrier to invading pathogens and/or increasing the total soluble phenolic compound concentration of orange peels.

Medicinal plants have various phytochemical compounds that are involved in membrane disruption, inhibition of essential metabolic function stresses on pH homeostasis through the accumulation of anions within the cell and the activation of defence mechanisms in fruit [173,174]. These phytochemicals are effective growth inhibitors of various phytopathogenic fungi in vitro. In fruits such as citrus, fungal pathogens grow better in acidic to neutral conditions than in alkaline conditions. In such instances, pathogens such as *P. digitatum*, which require an acidic environment, expend more energy on fungal acid production than a hyphal extension, and therefore growth may be inhibited [175,176]. Inhibition of *G. citri-aurantii*, *P. digitatum* and *P. italicum* by medicinal plant extracts may be caused by alteration of cell membrane function and cell transport function, inhibiting enzymes and protein synthesis and uncoupling of oxidative phosphorylation in mitochondria [176]. The pH of medicinal extracts is important for controlling postharvest citrus diseases because it directly affects the germination of conidia [60,173] and influences the virulence of pathogens through their colonization of host tissue [174].

Yusoff et al. [177] observed the antibiotic mechanism action of antifungal compounds of the bitter leaf (*V. amygdalina*) extract on the fungal inhibition under a scanning electron microscope (SEM). The hyphae of *B. cinerea* exposed to the phytochemical compounds of bitter leaf extract revealed alterations in the hyphal morphology. The mycelia became twisted and folded with a jagged edge. Some mycelia were agglutinated, with withered hyphae tips and the shrinkage of conidia after the treatment. This could prevent the dispersion of the gray mold disease of fruits to the adjacent fruits since the asexual spores of *B. cinerea* are abundant and easily dispersed. The morphology alteration of fungus was related to the secondary metabolites from the plant extract that acted as antifungal compounds to restrict the fungal growth. The composition of antifungal compounds acted as synergistic effects in controlling the *B. cinerea* development.

According to Ugboko et al. [151] and Yang et al. [178], in an oxidative sequence, antioxidants can act by (1) decreasing localised oxygen concentration; (2) preventing chain initiation by scavenging initiating radicals; (3) binding metal ions that can decompose lipid peroxides to peroxy and alkoxy radicals; (4) decomposing peroxides by converting them to non-radical products such as alcohols; and (5) chain-breaking by scavenging intermediate radicals such as peroxy and alkoxy radicals to prevent continued hydrogen abstraction. Chain-breaking antioxidants are often phenols or aromatic amines. In postharvest of horticultural crops and the food industry, an antioxidant is defined as a substance that, in small amounts, is capable of preventing or delaying the oxidation of easily oxidisable materials, such as fats [179].

Medicinal plants have polyphenols such as flavonoids and phenolic compounds that act as a reactive species scavenger, lipoxygenase inhibitor or reducing agents for metmyoglobin [180]. The alkaloids found in medicinal plants are known to interact with reactive species by trapping them with hydroxyl groups in their structure, while their chelating effect on ferrous ions can be attributed to the presence of nitrogen moiety [181,182]. Terpenoids and saponins from different medicinal plant extracts have been found to inhibit

the formation of reactive oxygenated species and exert their activity by inhibiting lipid oxidation and reducing oxidative stress [183,184].

## 6. Conclusions and Future Prospects

Studies on medicinal plant extracts have revealed thousands of phytochemicals with inhibitory effects against plant pathogens. Thus there is a need to study medicinal plants used in indigenous knowledge systems (IKS) that are known to have high antimicrobial and/or antioxidant capacity. Different extraction procedures can be applied to determine the composition of the different medicinal plants, and the identified molecules should be safe for use in crop protection and preservation of horticultural crops. Recent advances in postharvest protection and preservation of horticultural including nanotechnology, edible coatings and/or films should be used to incorporate medicinal plant extracts in the matrix. Moreover, the impact of the treatments on the sensorial characteristic of the treated products should be contemplated. Emphasis should be placed on minimizing human health risks and environmental toxicity while providing appropriate tools to tailor a complete pre- and postharvest pathogen management strategy. It is necessary to enhance the knowledge of the influence of medicinal plants and the final content of the chemical components to minimize undesirable variation or the low effectiveness of these compounds in the products.

**Author Contributions:** Conceptualization, O.A.F.; investigation, K.A.N.; resources, O.A.F.; writing—original draft preparation, K.A.N., writing—review and editing, O.A.F. and A.O.A.; supervision, O.A.F. and A.O.A.; project administration, O.A.F.; funding acquisition, O.A.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors are grateful to the University Research Committee at the University of Johannesburg for financial support.

**Acknowledgments:** This work is based on the research supported wholly or in part by the National Research Foundation of South Africa (Grant Numbers: 129295).

**Conflicts of Interest:** Authors declare no conflict of interest.

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