International Journal of Horticultural Science and Technology

Journal homepage: https://ijhst.ut.ac.ir

Potential of Plant Extracts as Biostimulants and Application at Different Production Stages of Selected Vegetables: a Mini-Review

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ARTICLE INFO

Article history:

Received: 4 June 2024,
Received in revised form: 19 May 2025,
Accepted: 21 May 2025,

Article type:

Review

Keywords:

Antifungal properties,
Antimicrobial properties,
Phytohormones,
Seed germination,
Shelf life,
Vegetative growth,
Yield

ABSTRACT

Plant extracts have emerged as promising biostimulants in agriculture, offering natural and sustainable alternatives to traditional inputs. Derived from various plant species, these extracts contain bioactive compounds that positively influence seed germination, enhance plant growth, and improve both productivity and nutritional composition. Their application has also shown potential in extending fruit shelf life by suppressing pathogen growth. However, challenges remain in standardizing extraction processes, and significant knowledge gaps exist regarding their optimal application. This review provides an overview of recent findings on the use of plant extracts as biostimulants or edible coatings, focusing on their application methods for vegetables where the edible part is the fruit. It emphasizes the reasons behind observed differences in results among similar studies, highlighting the need for further research to maximize the effectiveness of plant extracts as eco-friendly biostimulants in sustainable agriculture.

Introduction

Plant products and their analogues have long been recognized as essential sources of bioproducts for promoting plant growth, controlling insect pests, improving fruit quality, and extending the shelf life of fresh produce (Zulfiqar et al., 2020; Tavares et al., 2021). For example, commercially available products such as Biogrow, Bioneem, and Growel Organic Neem are derived from neem, while Kelp Green and Sea Rock are based on seaweed. Phytostim, a recently developed mixture of extracts including moringa, is specifically designed to improve plant growth and yield.

Historically, farmers have relied on synthetic chemical inputs to enhance crop yields and quality. However, this approach is increasingly seen as unsustainable in modern agriculture (Ahmad et al., 2020; Najarian and Souri, 2020). Synthetic fertilizers are no longer capable of addressing the concurrent challenges faced by the agricultural sector, such as a rapidly growing global population and the negative environmental impacts on ecosystems (Shooshtari et al., 2020). Additionally, inappropriate use of synthetic chemicals poses risks to human health, degrades ecological quality, and incurs high costs, prompting a growing interest in finding sustainable, natural alternatives.

Plant-based biostimulants have garnered attention as eco-friendly solutions working through complex biochemical interactions. These include stimulating enzymatic and hormonal activity and triggering plant defense mechanisms (Zulfiqar et al., 2020). Such biostimulants serve multiple purposes in crop production, including enhancements in plant growth, greater resistance to abiotic and biotic stress, and increasing nutrient use efficiency (Youssef and Giuseppe, 2020).

Furthermore, research has demonstrated that postharvest crop quality is influenced not only by preharvest conditions but also by agronomic inputs applied during growth and development (Koukounaras et al., 2020; Shooshtari et al., 2020). Although the precise mechanisms through which plant extracts function as biostimulants to improve plant growth, yield, and fruit quality remain to be fully elucidated, they are known to offer several advantages. These include enhancing nutrient uptake and assimilation, boosting antioxidant defenses and secondary metabolite production, increasing photosynthetic activity, improving water relations, and enhancing soil characteristics (Cristofano et al., 2021).

Fruits and vegetables, defined as “edible parts of plants either cultivated or harvested wild, in their raw state or a minimally processed form” (FAO, 2020), are particularly significant due to their high nutritional value. They contain a wide range of micronutrients and bioactive compounds, including dietary fiber, minerals (potassium, calcium, magnesium), vitamins (A, C, and E), and phytochemicals (polyphenolic compounds, carotenoids, glucosinolates), all of which are essential for human health (Hosea et al., 2018; Souri and Dehnavard, 2017).

The FAO/WHO (2018) recommends a minimum intake of 400 g of fruits and vegetables per person per day. Promoting increased consumption of these foods not only enhances human health but also necessitates increased production while mitigating the health and environmental risks posed by conventional agricultural inputs. However, fruits and vegetables are highly perishable, making it crucial to develop new techniques and products that simultaneously increase yield and improve quality.

Although numerous studies have reported the positive influence of plant extracts on crop productivity and quality, adoption of these findings by the farming community remains low. This gap may stem from a lack of standardized protocols for extraction and application. In this review, we explore recent advances in the development, application, and efficacy of plant extracts as biostimulants. The review highlights the impact of extraction methods on research outcomes and focuses specifically on vegetable crops, where the edible part is primarily the fruit. This includes members of the *Solanaceae* family [tomatoes (*Solanum lycopersicum*), chillies (*Capsicum frutescens*), bell peppers (*Capsicum annuum*), and eggplants (*Solanum melongena*)] and okra (*Abelmoschus esculentus*, Malvaceae).

Seed germination represents a key phase in the plant life cycle, as it directly influences crop plant density and, ultimately, profit margins. This complex process is regulated by multiple signals and is affected by both intrinsic factors, such as seed dormancy and nutrient availability, and extrinsic abiotic factors (Savaedi et al., 2019). Seed treatments using synthetic or natural compounds are aimed at enhancing the uniformity and vigor of seedlings while also boosting plant tolerance to abiotic stresses (Campobenedetto et al., 2020). Several studies have explored the efficacy of plant extracts in addressing these challenges (Table 1). For instance, tomato seed germination and seedling vigour were significantly improved when seeds were soaked overnight in aqueous garlic extract (10% w/v) before sowing (Rawal and Adhikari, 2016). Similarly, Hayat et al. (2018) demonstrated that applying garlic extract (10% w/v) as a foliar spray or via fertigation enhanced plant height, leaf area, and fresh weight of tomato seedlings. Following a comparable protocol, Ali et al. (2019) observed that a single foliar application of aqueous garlic extract (10%) improved the growth of eggplant seedlings. However, frequent applications—such as spraying three times a week—induced stress in seedlings and caused lipid peroxidation.

The beneficial effects of garlic extracts have been attributed to increased levels of carbohydrates, photosynthetic pigments, and soluble sugars in treated plants (Hussein et al., 2015). However, excessive concentrations or frequent applications of garlic extracts have been shown to induce phytotoxicity (Talukder et al., 2015; Cheng et al., 2016). Some bioactive compounds present in botanical extracts can inhibit seed germination by blocking the hydrolysis of nutrient reserves and interfering with cell division. This is achieved through the modulation of specific enzymatic and hormonal activities, which may significantly reduce plumule and radicle growth in various crops (Isfahan and Shariati, 2007).

In another study, Hala et al. (2017) prepared a standard moringa leaf extract by drying 1,000 g of fresh leaves and mixing them with 1 L of 80% aqueous ethanol. Pepper seeds were soaked in varying concentrations (2, 4, and 6%) of this extract for 6 h. The 4% concentration was found to significantly enhance germination percentage, germination rate, index, and coefficient of germination velocity, as well as improve seedling parameters. Conversely, Vyas and Sharma (2021) reported phytotoxic effects on tomato seed germination and growth when seeds were soaked for 30 min in alcoholic moringa extracts at concentrations of 1.5, 2, and 2.5%.

Table 1. Seed germination and seedling response to various plant extract treatments.

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Aloe vera	4 kg soaked in 4 L of water for 72 h Applied conc.: 50%, 100%.	foliar spray once a week for 6 weeks	Eggplant	• Treated seedlings were significantly taller than the control. • Seedlings sprayed with 100% extract had a significantly higher number of leaves than those sprayed with 50% extract and water	Wilson (2020)
Gingiber officinale (ginger) *Allium cepa* (garlic)	The extraction of samples was prepared by soaking the dry and powdered materials in distilled water (1:10 w/v) for 24 h at room temperature	Seeds were treated with extracts overnight	Tomato	• *Z. officinale* showed greater seed germination and seedling vigour than both the control and seeds treated with *Allium cepa*	Rawal and Adhikari (2016)
Allium tuncelianum	96% ethyl alcohol was added as 50 mL alcohol g^{-1} garlic and kept at 25 °C overnight and filtered. Ethyl alcohol in the filtrate was evaporated using a rotary evaporator at 35 °C. Applied conc.: 0.5, 1, and 1.5%	10 mL extracts of $plant^{-1}$ were applied using a hand sprayer to seedlings at the two- or three-leaf stage	Tomato Pepper	• Higher doses of extract reduced the disease severity *of Botrytis cinerea, Fusarium oxysporum f.sp. lycopersici, Pythium defence, Rhizoctonia solani and Sclerotium rolfsii* • The extract applications increased the number of phenolic compounds in tomato	Ozkaya and Ergun (2017)
Aegle marmelos *Phyllanthus emblica* *Terminalia belerica* *T. arjuna* *T. chebula* *A. indica*	200 g of fresh leaves cut into 1 L reagents bottle separately after blending with a blender, 800 mL of water was added to the bottle and kept for 72 h	200 mL of each aqueous extract were applied in each pot at planting and after 10 d	Okra	• *T. arjuna* significantly increased the germination and growth of okra • *A. indica* inhibited the germination percentage and growth. • The inhibitory effect of *T. chebula* was also observed on plant growth	Talukder et al. (2015)

Table 1. Seed germination and seedling response to various plant extract treatments (continued).

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Monsonia burkeana *M. oleifera*	100 g was added separately to 700 mL methanol and placed on a rotary shaker for 24 h. Applied conc.: -0.4, 0.6, and 0.8 g mL^{-1} for *M. burkeana* - 0.2, 0.4, and 0.6 g mL^{-1} for *M. oleifera*	Soil treatment with each plant extract solution was done once after 7 d of inoculation	Tomato	• *M. burkeana* significantly *reduced R. solani* growth at 8 g mL^{-1} (71%) relative to control, whilst *M. oleifera* extract reduced pathogen growth by 60% at a concentration of 6 g mL^{-1}. • Both plant extracts also reduced pre- and post-emergence damping off incidence	Hlokwe et al. (2020)
Turmeric Cardamom (*Elletaria cardamomum*), Cinnamon Lemongrass Ginger Clove (*Syzygium aromaticum*) Black pepper	Powders separately soaked in ethanol (1:1.5 (w/v)) for one week. Ethanolic spice extracts were subjected to 1:9 dilution of sterile distilled water. Applied conc.: 10, 20, 30, and 40%	seeds soaked overnight in each of the spice extract concentrations	Tomato	• Clove, turmeric, ginger and black pepper were active in inhibiting the growth of all the pathogens by about 81%. • High germination percentages of up to 99% were recorded in seeds treated with all extract diluted by 30 and 40% except clove	Lengai et al. (2021)
Achillea millefolium, *Salvia verticillata Ziziphora clinopodioides*	40 g of powder materials from each plant were added to 400 mL of methanol and homogenized for 24h Applied conc.: 1, 1.5, and 2, mg mL^{-1}	Prior to transplanting, roots were soaked in fungal spore suspension. Then, plant extracts were added to each pot	Tomato	• Z. clinopodioides demonstrated the highest antifungal activity against mycelial growth of F. oxysporum strain et al. l concentrations • All plant extracts increased the plant height and fresh and dry weight of root and shoot with the consequent reduction in the disease symptoms of seedlings	Maddahi and Nematollahi (2019)

Table 1. Seed germination and seedling response to various plant extract treatments (continued).

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Lycium arabicum	Aqueous extracts: 150 g or 300 g of stem and fruit powder soaked in 1 L for 24 h. Organic extracts, 100 g of the powdered samples extracted with MeOH–H_2O (7:3) (v/v) for 72 h at room temperature. Applied conc.: 1, 2, 3, and 4%	1. Ten imbibed seeds were separately placed on the filter paper, and 5 mL of extract was added 2. Seedlings were drenched with 25 mL of aqueous extracts	Tomato	• Butanolic extract, at 4%, was the most active, inducing a 41.4% reduction in *Fusarium oxysporum f. sp. radicis-lycopersici)* mycelial growth. • Aqueous extracts at 4% inhibited *Fusarium oxysporum f. sp. radicis-lycopersici)* radial growth as compared to control • All *L. arabicum* aqueous extracts significantly improved germination and enhanced growth compared to the control	Nefzi et al. (2017)
Neem Tumeric	The powder was mixed with petroleum (125 g L^{-1}). The extract was then mixed with 5 L of water to prepare the final solution for application.	The first spray was applied after the appearance of pests. A total of six applications, on average, 10 d for each application	Okra	• There was a significant reduction in pests in all treatments as compared to the control. • Neem was more effective than turmeric. • Both extracts were more effective than synthetic pesticides in controlling okra pests and stimulating growth and yield	Muhammad et al. (2018)
Neem leaf (1:1 w/v), Garlic clove (1:3 w/v), Ginger (1:2 w/v) Allamonda leaf (1:1 w/v)	100 g material was added to 100 mL water (1:1, w/v) 200 mL of water added to 100 g material (1:2, w/v) 300 mL of water added to 100 g plant parts (1:3, w/v)	Seeds were treated for 1 h and placed on moistened blotter paper	Chili	• All seed-treating agents were effective compared to control in controlling seed-borne fungi • The highest percentage of healthy seedlings was recorded in seeds treated with allamanda leaf extracts • The highest vigour index occurred when the seeds were treated with neem	Alam et al. (2014)

In their investigation, Vyas and Sharma prepared a 50% crude extract by dissolving 20 g of dried, powdered plant material in 50 mL of alcohol and allowing it to stand for 24 h. The observed phytotoxicity in this study could be partially attributed to the solvents used for extraction. While alcohol is highly effective at extracting phytochemicals, it may not always be suitable for preharvest applications (Emongor et al., 2015; Abdel-Rahman and Abdel-Kade, 2020). Further research is needed to optimize extraction protocols and evaluate their compatibility with agricultural practices.

Khanam et al. (2020) investigated the potential of neem extract to enhance seed germination in three vegetable crops: cucumber, chilli, and eggplant. The crude extract was prepared by grinding 500 g of fresh neem leaves, which was then diluted to obtain concentrations of 3, 6, 9, and 12%. Their findings indicated that while higher concentrations of neem extract (above 9%) reduced germination percentages compared to the control, lower concentrations (below 12%) positively influenced seedling traits such as shoot and root length and weight.

In contrast, Utobo et al. (2015) reported that a 12% neem solution prepared from dried leaves significantly improved cucumber seed emergence. A critical distinction between these two studies is the difference in preliminary sample preparation—using fresh versus dried neem leaves—which likely influenced the concentration of bioactive compounds in the final solutions (Krakowska-Sieprawska et al., 2022).

These findings partially align with an earlier study by Vaithiyanathan et al. (2014), which found that a neem extract prepared by mixing 100 mg of fresh neem material with 250 mL of water negatively affected okra germination rate, seedling quality, and biochemical parameters, including protein, starch, and amino acid content.

Neem trees are known for their diverse bioactive compounds, including nimbidin (with antibacterial and antifungal properties), salannin (a repellent), and azadirachtin (an anti-feedant and anti-hormonal agent) (Sankaram, 1987, as cited in Ashrafi et al., 2009). Additionally, compounds such as nimbolide B and nimbic acid B have been implicated in the phytotoxic effects observed at higher concentrations, potentially disrupting seed germination and growth (Kato-Noguchi et al., 2014).

These studies underscore the dual role of neem extracts in agricultural applications, with their efficacy being highly dependent on concentration and preparation methods. This highlights the importance of standardizing extraction and application protocols to maximize their benefits while minimizing adverse effects.

Vegetative growth and yield

Plant growth and development are heavily influenced by nutrient availability, with each plant species having an optimal nutrient range and minimum required levels. Botanical extracts have been shown to enhance soil properties (physical, chemical, and biological), promote root growth and development, induce stress tolerance (abiotic and biotic), and improve flowering and yield (Table 2).

Ullah et al. (2019) evaluated the impact of moringa extract on tomato growth and yield. In this study, a standard solution was prepared by grinding fresh moringa leaves with water in a 1:5 ratio, followed by filtration—the application of a 6% extract solution shortly after transplanting significantly enhanced tomato growth and fruit quality. Ngcobo and Bertling (2021) made similar observations. They prepared a standard extract by processing 20 g of dried moringa leaves with ethanol and applying it in concentrations of 20, 50, and 80% (extract/water). Unlike Ullah et al. (2019), who used the extract once (15 d after transplanting); Ngcobo and Bertling (2021) applied the extract weekly from two weeks post-transplanting until maturity.

While both studies reported positive effects of moringa extract on plant growth and fruit quality, attributing the observed improvements solely to a single application in Ullah et al. (2019) is debatable, as plants require nutrients throughout their development. A third study by Weerasingha and Harris (2020) found that weekly or biweekly foliar application of 10, 20, and 30% moringa leaf extract on chilli plants increased the number of pods per plant, seeds per pod, fruit length, leaf chlorophyll content, and total soluble solids compared to the control. In this study, the stock solution (100%) was prepared from dried moringa leaves, and a weekly 10% foliar application was identified as the most effective treatment.

These findings suggest that a consistent application schedule, such as once a week at moderate concentrations, can be recommended for optimizing the benefits of moringa extract. Numerous studies support the positive effects of moringa extract on vegetable production, including its application on peppers (Desoky et al., 2018), eggplants (Hoque et al., 2020; Musse et al., 2021), okra (Yusuff et al., 2020), and cucumbers (Ahmed et al., 2020), despite variations in extraction and application methods (Table 3).

Table 2. Influence of plant extracts on growth parameters and yield performance of cultivated plants.

Plant extract	Extraction method	Application	Crop	Key findings	Authors
Turmeric	300 g of dried turmeric soaked in 600 mL ethanol or water. Then, 1L of distilled water was added to the filtrate to dilute the extract Applied conc.: 1, 2, and 3%	Treatments were applied two weeks after planting, repeated at 4, 6, 8, 10, and 12 weeks at a rate of 20 mL $plant^{-1}$	Okra	• Aqueous extract improved the plant height, number leaf, stem girth, leaf area, and leaf area index than ethanol turmeric extract • 2% aqueous and ethanol extract had significantly higher yields	Ogbuehi et al. (2017)
Malva parvflor *nutrients*	Plants were cut before flowering and were immersed in water (1:5) in tightly closed barrels insulated from air for 20 d, and were then filtered Applied conc.: 50%, 75%.	An average of 4 sprays of both concentrations until moisture saturation after adding tween-20 as a spreading substance	Eggplant	• Extract at 75% and the nutrients significantly improved most of the study parameters, including leaf nutrient content, vegetative growth traits, and yield • A combination of 50% *Malva park flora* and nutrients significantly affected nitrate reductase activity and total soluble solute	Allawi et al. (2017)
Annona squamo (Linn) *Moringa oleifer* (Lam)	Plants were crushed and soaked in 10 L of ethanol and acetone for 12 h separately; 33.3% of active ingredients were diluted with adjuvants, such as texapon (11.11%), nitrosol (22.22%), salt (22.22%), and black soap (11.11%). Applied conc.: 1:9 v/v	Foliar application (target crop as well as insect pests) The four-weekly application was made at seven d intervals	Okra	• Ethanolic plant extracts had higher insecticidal efficacy than acetonic extracts • The yield of plots treated with ethanolic plant extracts was twice as much as that of acetonic extracts.	Olaniran et al. (2016)

Table 2. Influence of plant extracts on growth parameters and yield performance of cultivated plants (continued).

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Nicotiana tabacum *Aegle marmelos* *Ficus hispid* *Lawsonia inermis,* *Vitex negundo* *Carum roxburghianum* *Corchorus capsularis* *Swietenia macrophylla* *Allium sativum*	100 mg of leaf dust or grinding seeds were dissolved in 1 L of tap water	The extract was sprayed on the eggplant experimental plot twice a week with the help of a sprayer	Eggplant	• *N. tabacum* extract showed excellent performance against pest attacks, while *A. Sativa* extract showed an inferior efficacy • *S. macrophylla* and *C. roxburghianum* seed extracts hampered plant growth • *N. tabacum* enhanced the plant growth, yield, and longevity of eggplant • *A. sativum* and *C. roxburghianum* caused total inhibition of fruit production	Azad and Sarker (2017)
Costus speciosus *Tagetes patula Helichrysum bracteatum*	The root of *C. speciosus* and the fresh leaf samples of *T. patula* and *H. bracteatum* were air-dried and powdered Applied conc.: *C. speciosus*: 3.2% *T. spatula*: 5.3% *H. bracteatum: 5.5%*	Two rounds of foliar applications using 20 L backpack sprayers were administered at dusk. All the tested compounds were reapplied 10 d after the first application.	Sweet pepper	• All extracts significantly reduced populations of *Tetranychus urticae* over the control and were as effective as the standard check (abamectin) • All treatments showed marked elicitor effects on the sweet pepper defense system with elevated photosynthetic pigment, total phenol, and protein levels and enhanced antioxidant enzyme activity and total yield	Ismail et al. (2022)
Capsicum frutescens *Hyoscyamus niger Melia azedarach Xanthium strumarium* *Achillea wilhelmsii*	Each plant extract was prepared in 200 g 200 mL^{-1} ethanol Applied conc.: 3, 6, and 12%	Eggs or second-stage juveniles of *Meloidogyne javanica* were applied to the root (~2 cm depth of the soil), and 5 mL of extract was added by a syringe into the soil	Eggplant Sweet pepper	• *H. niger* and *X. strumarium* at 12% concentration were more efficient than *M. azedarach, C. frutescens,* and *A. wilhelmsii* extract on egg hatching of both plants • No significant difference was found among nematode mortality and growth parameters of both crops	Kepenkci and Salam (2018)

Table 2. Influence of plant extracts on growth parameters and yield performance of cultivated plants (continued).

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Curcuma longa, *Lantana camara* *Capsicum frucetense* *Cubeba sureboa.*	250 g of rhizome was macerated into 80% ethanol and 20% of water, stored for 24 h and sieved	Extracts are applied using a backpack knapsack sprayer starting from 15 d after transplanting.	Eggplant	• Hot chilli and *Lantana* had the highest reduction in fruit and shoot borer, followed by *C. seriboa and C. Longa,* respectively • All extracts showed par to the standard check • The highest marketable fruit yield was obtained with hot chilli, followed by *L. camara*, standard check, and other extracts as compared to the control	Duza et al. (2019)
Calendula officinalis *Mentha viridis* *Salvia rosmarinus*	The dried powder was used to prepare 30% of the stock solution of each plant. The mixtures were stirred at three h intervals for 24 h Applied conc.: 15, 30, and 45%	The number of *Myzus persicae* marked leaves was counted 1 h before bioassays Aphids on pepper plants sprayed at 3, 6, 9, and 12 d, after spraying, the number of living aphids were counted	Pepper	• All treatments reduced the number of aphids • *C. officinalis* extract is more effective than those of *M. viridis* and *S. rosmarinus*	Mdellel et al. (2021)
Water gourd (*Lagenaria siceraria*), Eucalyptus (*Eucalyptus chamadulonsis*), Garlic Babla (*Acacia nilotica*) Black cumin (*Nigella sativa)*	100 g of plant material was boiled in 1000 mL distilled water (w/v, 1:10) for 45 min and then passed through two layers of cheesecloth Applied conc.: 2.5, 5, and 10%	Plant extract sprayed twice a week	Tomato	• Number of branching was highest in treatment with black cumin (5%) and lowest in garlic (10%) and babla (2.5%). • A maximum number of late blight-affected leaves was found in control and garlic (5%), and the minimum in black cumin (10%). • Yield was highest in black cumin (5%) and lowest in garlic (5%) treatment	Islam et al. (2019)

Table 2. Influence of plant extracts on growth parameters and yield performance of cultivated plants (continued).

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Azadiracata indica *Datura stramonium* Garlic *Ocimum santum* *Eucalyptus globolus*	50 mg leaves blended without water, pulverized leaf tissue filtered, and 100% pure filtrate was used as an extract in a 1:1 ratio (w/v) Applied conc.: 5%	The foliar spray was started at the onset of the disease, and two sprays were repeated	Tomato	• Garlic and datura extract had the highest reduction of disease intensity compared to the control (mancozeb, 0.2 and the control • Maximum yield reported in garlic-treated plants	Bhagat and Zacharia (2018)
Calotropis procera	10 g of dried samples for 1.5 min and 100 mL of sterilized distilled water added and blended again Applied conc.: 5, 10, and 15%	Seeds were soaked in each extract concentration, and seeds were soaked in a suspension of the isolate of Fusarium KAUK7 as the infected control. The third group had the seeds soaked in sterile distilled water	Tomato	• In all concentrations, the extracts suppressed the growth of the pathogen • The highest reduction of mycelial growth was obtained with a 15% extract • 5, 10, and 15% significantly enhanced the fresh and dry weights Total phenols and flavonoids, as well as antioxidant enzymes, increased in inoculated or non-inoculated tomato plants after the treatment	Abo-Elyousr et al. (2022)
Nerium oleander *Eucalyptus chamadulonsis* *Citrullus colocynthis*	10 g of fresh leaves were crushed in 100 mL of sterile water or ethanol (1:10 w/v) Applied conc.: 15%	Four-week-old seedlings inoculated with bacteria (PHYXV3) by spraying each plant with 20 mL of the pathogen solution. Two d after inoculation, tomato seedlings were treated with a 15% v/v of each extract and kept under greenhouse conditions	Tomato	• Plant extract significantly reduced disease severity and increased the shoot weight of tomato as well as the total phenol and salicylic acid content of tomato plants • *C. colocynthis* and *E. chamadulonsis* significantly increased peroxidase activity, while only *E. chamadulonsis* increased polyphenol oxidase after infection with the causal agent	Abo-Elyousr et al. (2020)

Table 2. Influence of plant extracts on growth parameters and yield performance of cultivated plants (continued).

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Moringa	100 g fresh material 500 mL^{-1} distilled water Applied conc.: 20%	Eggplant plants were foliar sprayed with MLE every two weeks during the experiment.	Eggplant	• MLE significantly improved N, P, K, Ca, Mg and Fe content of fruits compared to control plants • MLE increased plant productivity	Musse et al. (2021)
Moringa	200 g of ground seeds put in 2L of 80% ethanol and vigorously stirred on a shaker for 5 h Applied conc.: 0.5%	1- Foliar sprays three times: 20, 35, and 50 d after transplanting to run-off. 2- Rhizosphere application: 200 L extract ha^{-1} to drip irrigation water three times with the 2nd, 4th, and 6th irrigation	Pepper	• All treatments significantly increased plant growth and yield, contents of leaf photosynthetic pigments, free proline, total soluble sugars, N, P, and K+, ratio of K+/Na+, and activities of CAT, POX, APX, SOD and GR, • Significantly reduced contaminants: Na+, Cd, Cu, Pb, and Ni contents in plant leaves and fruits compared to the control	Desoky et al. (2018)
Moringa	10 kg of leaves crushed in 1 L of water followed by filtering Applied conc.: 0, 4, 8, and 12%.	The extract was applied to soil-filled polybags	Pepper	• Fresh and dry weight increased as the extract percentage increased • Protein, fats, carbohydrate, ash, lycopene, vitamin A, and vitamin C contents increased parallel to growing levels of extract	Ansa and Ansa (2021)
Moringa	20 g of moringa leaves were mixed with 675 mL of 80% ethanol Applied conc.: 1:32 (v/v)	The extract was applied one week and two weeks after transplanting	Sweet pepper	• Plant height, number of leaves, fruit weight and yield of sweet bell pepper were significantly influenced by the application of moringa leaf extract	Dunsin and Odeghe (2015)
Liquorice	Ground roots at concentrations of 2, 4, and 6 g L^{-1} macerated in hot water at 40 °C for 24 h	Spraying treatments were started after 20 d of transplanting, at four times with 10 d intervals	Eggplant	Extract at 6 g L^{-1} increased growth, percentage of mineral content in leaf (N, P, and K) and yield of eggplant under saline conditions	Ramadan et al. (2016)

Table 2. Influence of plant extracts on growth parameters and yield performance of cultivated plants (continued).

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Karamja (Pongamia pinnata) *Garlic* *Neem* *Mehogoni (Swietenia macrophylla)*	Plant samples were ground in distilled water at 100 g L^{-1} (10%) in a blender and filtered	The first spray done after 30 d of transplanting. The plant extracts sprayed 3 times at 15 d intervals	Okra	• All phyto-pesticides performed better than the control • Karanja extract-treated plants had the minimal rate of viral incidence (*Okra mosaic*), the highest plant height, flower count, and yield	Bhyan et al. (2018)
Cinnamon	5 g added to 1 L of warm tap water and filtered through a flour mesh. Applied conc.: 0.5%	In the glasshouse: plants inoculated by foliar spray with a water suspension of *B. cinerea* spores (1 mL $plant^{-1}$). 3 and 6 d after inoculation, filtrate sprayed on the plant surface In the field, six sprayings of filtrates applied at 4–5 d intervals	Tomato	• Cinnamon filtrates positively influenced the growth of plants both in the greenhouse and the field • Antifungal activity (against *Botrytis cinerea*) of cinnamon was proved in greenhouse tests • The fresh weight of non-inoculated tomato plants treated with cinnamon filtrates was significantly higher than the control	Kowalska et al. (2022)
Moringa	30 g of fresh leaves with 300 mL of distilled water mixed in a household blender for 15 min Applied conc.: 1:20, 1:30, and 1:40	Extracts were applied three times as foliar spray at 30, 45 and 60 d after transplanting	Cucumber	• Cucumber growth traits (plant height, leaf area, number of leaves, weight of leaves and stems) and flowering traits (number of flowers, d to the first female flower and fruit set %) were significantly enhanced • Treatments markedly increased the endogenous hormone levels and enhanced the activity of the antioxidant enzymes in cucumber leaves	Ahmed et al. (2020)

Table 3. Potential of plant-derived treatments for enhancing postharvest quality and storage stability of fruits.

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Azadirachta indica *Vernonia amygdalina*	100 g plant material in 1 L of distilled water in separate flasks and left to stand for 48 h. Applied Conc.:10%	Fruits were dipped in extracts for 5 min and air dried, after which the pathogen *Colletotrichum capsici* was inoculated using a 1 mm agar plug from the pure culture of *C. capsici*.	Pepper	• Extracts of *A. indica* and of *V. amygdalina* significantly reduced the lesion diameter of *C. capsici* and decay • Total soluble solid (TSS) of fruits treated with the extract of *A. indica was* lower than that of the control	Ekhuemelo et al. (2018)
Neem Beeswax	200 g of the powder soaked in 1000 mL of distilled water for 6 h Applied Conc. (neem): 15, 20, and 25% Beeswax: 3, 6, and 9%	Fruits dipped in the Neem leaf extract solution for 5 min and surface air dried and treated with the beeswax coating material	Tomato	• BW9*NLE25 significantly extended the shelf life of fruits by eight d and effectively reduced weight loss, increased titratable acid (TA), PH, TSS • BW9*NLE25 maintained higher marketable fruits while reducing the percent decay by 96.1% compared to untreated fruits.	Zewdie et al. (2022)
Annona muricata *Hibiscus sabdariffa*	10 g of the plant extracts dissolved in 100 mL (10% w/v) ethanol Applied conc.: 3, 5, 6, 9, and 12%	1. Tomatoes were allowed to soak in the extract for 30 min 2. Coating each tomato was coated with powder	Tomato	• *A. muricata is* most effective in preserving up to 50% of the tomatoes after 35 d • 6% (w/v) of *A. muricata* resulted in a preservation rate of 75% of the tomato fruits	Banjo et al. (2022)
Neem leaf Garlic bulb Ginger	40 g L^{-1} of the powdered material dissolved in 1 L of distilled water separately, vigorously agitated and left for 24 h Conc.: 40 g 100 mL^{-1}	Tomatoes were dipped into the solutions of various plant extracts for 1 min at room temperature and air-dried. Treated tomatoes were stored for 12 d at 25 °C	Tomato	• The extract reduced mycelia growth, extended shelf life and maintained the quality of tomato fruits during storage • Ginger extract was the most effective in preventing tomato rot disease	Tunwari et al. (2019)

Table 3. Potential of plant-derived treatments for enhancing postharvest quality and storage stability of fruits (continue).

Plant Extract	**Extraction method et concentration**	**Method of application**	**Crop**	**Key findings**	Authors
Liquorice Garlic	Garlic: 4% Liquorice: 0, 2, 4 g L^{-1}	Fruit cleaned and soaked in different solutions	Tomato	• Extracts significantly reduce the percentage of decay and weight loss as compared to untreated fruits • Liquorice extract increased TSS • Combined treatment with garlic and liquorice was more efficacy	Taain et al. (2017)
Garlic	Garlic extract (2%) was prepared by grinding the cloves and mixing it with distilled water	Fruits were kept in the chemical-treated bags	Tomato	• Coating reduced weight loss compared to the control. • 10% spoilage after 21 d of storage for treated fruit, while it started much earlier with the control (15^{th} d)	Abrol and Kumar (2019)
Aloe vera	*A. vera* gel was collected from fresh leaves of aloe plants, and the colourless gel was homogenized in a blender. Applied conc.: 0.1, 0.5, 1.0%	Fruits were dipped at ambient temperature for 10 min	Eggplant	• 0.5% Aloe coating at 10°C showed a significant effect and delayed the changes in weight loss, shrivelling, TSS, pH, sugar increased and firmness, stem colour, acidity, reducing sugar, vitamin C	Amanullah et al. (2016)
Aloe vera chitosan	The gel was crushed in a blender to yield and then filtered to remove the fibrous fraction. Gel and chitosan were diluted to 2% (v/v) using distilled water. Combined coating of 1% *A. vera* gel and 1% chitosan	Fruits were immersed in a solution for 5 min at 20 °C	Tomato	•All three treatments increased the TSS, total phenolic content, and pectate lyase activity and gradual decreases in the TA and ascorbic acid content induced antioxidative activities. •Combined *A. vera* gel and chitosan showed the best efficiency in delaying the ripening process and extended the fruit shelf-life up to 42 d	Khatri et al. (2019)

Table 3. Potential of plant-derived treatments for enhancing postharvest quality and storage stability of fruits (continue).

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
Aloe vera	Leaves were cut open, the gel was scraped, homogenized using a mixer, and sieved through 45 µm mesh	The coating was made by dipping fruits in the gel for 5 min and leaving them to dry under tropical room conditions for 1 h.	Eggplants	• Treatments resulted in the accumulation of phenolic compounds and ascorbic acid, which increased the antioxidant capacity of the fruit	• Dadzie et al. (2022)
T2: Aloe vera and thankuni (*Centella asiatica* T3: Onion, garlic and ginger extracts *T4: Aloe vera*, thankuni, onion, garlic and ginger extracts	One kg of plant materials was blended and then filtered. To prepare the combination of the extracts, an equal amount of each single extract was taken, and the mixture was made to reach 40 mL.	Fruits treated with specific treatments were done by spraying	Eggplants	• In comparison to the control (T1), the postharvest properties were well maintained in T4-treated eggplants as recorded accordingly for shelf life, vitamin C, microbial infection, rate of pH reduction, loss of fresh weight, and colour and firmness scores • T4 was more suitable	• Pervin et al. (2019)
Moringa oleifera *Vernonia amygdalina*	Thirty g and 40 g of the powdered samples were dissolved in 100 mL of sterile distilled water, respectively, and allowed to stand for 72 h Applied conc.: 30 and 40%	Fruits inoculated by dipping in spore suspensions (*Rhizopus stolonifer, Fusarium oxysporum and Aspergillus niger*) for 5 min and incubated for 24 h at room temperature. Inoculated fruits immersed into extracts	Tomato	• In vivo, control of the fungal pathogen using both extracts proved effective • 40 g mL^{-1} of both extracts increased the shelf life of tomatoes, and the *V. amygdalina* gave the best result with 0.00% rot at 29 d after treatment	Yusuf et al. (2021)

Table 3. Potential of plant-derived treatments for enhancing postharvest quality and storage stability of fruits (continue).

Plant Extract	Extraction method and concentration	Method of application	Crop	Key findings	Authors
-40% pure *A. vera* Gel -40% Aloe Gel + citric acid -40% Aloe Gel + 10% -Neem+ citric acid -40% Aloe Gel + 20% Neem plus citric acid -40% Aloe Gel +10% Neem -40% Aloe gel + 20% Neem	Neem: the paste was added to water with 10% and 20% solution 40 gm of *Aloe vera* gel matrix was separated from the outer cortex of leaves, and this colourless hydro parenchyma was ground in a blender.	Fresh fruits were dipped in a coating solution at room temperature for 15 min	Tomato	• Pure *A. vera* gel and *A. vera* gel with 20% neem extract and coated tomatoes were maintained at pH 4, thus showing a delay in ripening and extending the shelf life up to 30 d, whereas the control deteriorated in a matter of 18 d	Kumar et al. (2016)

The observed improvements in plant growth and fruit quality have been attributed to the high cytokinin content in moringa extract, which enhances cell division and expansion. Additionally, the presence of ascorbate and calcium contributes to the cell wall structure and firmness of the fruit, further supporting the extract's effectiveness (Ullah et al., 2019; Ngcobo and Bertling, 2021).

Plants extract as pesticides, pest and disease management

The improvement in plant growth stages using plant extracts can often be attributed to their efficacy in managing pests and diseases (Table 3). Aqueous neem leaf extract (50% w/v) was found to inhibit the mycelial growth of *Fusarium oxysporum* in eggplant seeds by 50% (Jatav et al., 2019). Similarly, a 100% (w/v) aqueous neem extract demonstrated efficacy in treating chilli seeds, improving germination percentages and seedling quality (Alam et al., 2014). In another study, Soh et al. (2021) prepared a standard aqueous neem extract by grinding 200 g of fresh leaves in 1 L of water and diluting the solution to different concentrations (25, 50, 75%). The study reported that the lowest concentration (25%) was the most effective.

While all three studies used aqueous solutions from fresh neem leaves, the differences in the method of extract preparation could explain the variations in results. For example, Jatav et al. (2019) and Alam et al. (2014) prepared their extracts by mixing fresh leaves with water before grinding, whereas Soh et al. (2021) diluted a pre-prepared stock solution. Other factors, such as geographic location and plant age, may also influence the extract composition and its bioactivity.

Garlic extracts have also shown potential in pest and disease management. For example, an aqueous garlic extract (2.5%) reduced the larval population of *Tuta absoluta* in tomatoes by about 60% compared to the control. It increased total yield, phenolic content, and flavonoid levels in treated plants (Hussein et al., 2015). Similarly, cucumber seeds and seedlings treated with garlic extracts (4, 8, and 12% w/v) showed reduced incidence of damping-off and downy mildew diseases (Trabuco de Evert et al., 2015). Although the study by Trabuco de Evert et al. (2015) also demonstrated a 30% reduction in *Tuta absoluta* infection and increased tomato yields with garlic extract applications, details on the preparation of the extract were not provided. The efficacy of garlic extracts is attributed to compounds like oleoresins, volatile oils, and antifeedant substances such as allyl propyl disulfide and diallyl disulfide (Ghanim and Abdel Ghani, 2014).

The antimicrobial properties of ginger have also been explored. Lengai et al. (2021) reported that crude ginger extract, prepared by soaking ginger powder in ethanol (1:1.5 w/v) for one week and applied at concentrations of 10, 20, 30, and 40%, inhibited the growth of *Alternaria*, *Pythium*, and *Fusarium* in tomatoes by 54–100%. Additionally, weekly sprays of ginger aqueous extracts significantly suppressed the incidence and severity of downy mildew disease in cucumbers while enhancing growth (Utobo et al., 2015). Ginger's growth-promoting properties may be attributed to its diverse antioxidants and antimicrobial compounds, including gingerols, geranial, alpha-zingiberene, beta-sesquiphellandrene, aromatic-curcumene, and beta-bisabolene (Liu et al., 2019; Munda et al., 2018).

Despite its efficacy, the use of ginger as a plant growth enhancer poses challenges. Ginger is widely utilized in food and pharmacological industries, and increasing its demand for agricultural applications may strain its availability, potentially driving up prices and negatively impacting consumers. Therefore, its use should be balanced against economic and practical considerations.

Effects of plant extract on postharvest crop quality

Fresh fruits and vegetables are highly susceptible to spoilage, deterioration, and contamination by pathogenic microorganisms after being harvested (Sharma et al., 2009). Botanical extracts can be employed to preserve fruits and vegetables through dipping, fumigation, spraying, or incorporation into composite coatings. Utilizing organic products as preservation agents provides an eco-friendly alternative to synthetic fungicides, avoiding their hazardous effects and mitigating the development of pathogen-resistant strains (Santra and Banerjee, 2020). Among various preservation strategies, plant extract-based edible coatings have gained significant attention as substitutes for costly technologies and synthetic chemicals (Table 3).

Neem leaf aqueous extract (40 g L^{-1}), garlic extract, and ginger extract have proven effective in reducing fungal mycelial growth, extending shelf life, and maintaining the quality (firmness and weight) of tomatoes stored for up to 24 d at room temperature (Tunwari et al., 2019). Similarly, coating tomatoes with neem powder extended their shelf life from 15 d (control) to 22 d at room temperature (Hosea et al., 2018). Comparable findings were observed for okra fruits coated with neem powder (Ogbaji and Iorliam, 2020). These results suggest that neem when either applied as an extract or in powder form, offers comparable benefits for extending shelf life. However, further studies comparing these two forms of application could provide more clarity on their relative efficacy.

Moringa extracts and powders are also extensively utilized for shelf-life extension due to their antimicrobial and fungicidal properties (Tukur et al., 2021; Estiaque et al., 2022; Tunwari et al., 2019; Pervin et al., 2019). Ngcobo and Bertling (2021) demonstrated that postharvest treatments with 5% moringa leaf extract (MLE) or a combination of 5% MLE and hot water significantly improved the quality and extended the shelf life of cherry tomatoes. In another study, okra fruits coated with moringa powder retained better quality than those treated with neem powder (Ogbaji and Iorliam, 2020). One limitation of powder application, however, is the lack of precision in the quantity applied.

Aloe vera gel, known for its antioxidative and antimicrobial properties, has also shown remarkable potential for extending the shelf life of various foods. In addition to preserving quality, it offers therapeutic benefits (Maan et al., 2021). Aloe vera gel has been used alone or in combination with other commercial coatings, such as chitosan, methylcellulose, and beeswax, to enhance postharvest storage of tomatoes (Khatri et al., 2019; Chauhan et al., 2015) and bell peppers (Manoj et al., 2016). For example, coating eggplants with 0.5% Aloe vera-based solutions delayed ripening, maintained firmness, reduced weight loss, and minimized changes in pH, titratable acidity, vitamin C, and total soluble solids during storage (Amanullah et al., 2016).

Tomatoes coated with 10 and 15% Aloe vera gel exhibited reduced ethylene production and lower lycopene and β-carotene content, while a 20% solution increased total phenolics and antioxidative properties. However, parameters such as firmness, titratable acidity, weight loss, respiration rate, and fruit colour remained unaffected (Chrysargyris et al., 2016). Aloe vera gel is generally prepared from leaves through homogenization, filtration, and dilution (Chrysargyris et al., 2016; Pervin et al., 2019; Dadzie et al., 2022). In some studies, additional steps, such as pH adjustment with acidic substances, were included to enhance efficacy (Amanullah et al., 2016). However, the specific role of pH levels in determining the gel’s effectiveness remains unclear.

The antimicrobial activity and protective effects of Aloe vera gel are attributed to its bioactive compounds, including saponins, acemannan (a polysaccharide), and anthraquinone derivatives (Sánchez et al., 2020). Among these, aloe-emodin, an anthraquinone derivative, has been identified as a key contributor to the gel’s antioxidant properties (Farina et al., 2020). These findings underscore the potential of botanical extracts, particularly neem, moringa, and Aloe vera, as natural, cost-effective solutions for preserving fruits and vegetables while maintaining their quality and reducing postharvest losses.

Several medicinal plants have been evaluated for their potential to preserve fruits and vegetables, with notable success in suppressing postharvest decay. For instance, the efficacy of *Vernonia amygdalina* (bitter leaf) in controlling fruit decay has been demonstrated in tomatoes (Yusoff et al., 2021), peppers (Zakari et al., 2016), and okra (Ijato, 2022). A crude extract of *V. amygdalina* prepared by mixing 30 g of dried leaves with 100 mL of water and applied at various concentrations (0, 40, 60, and 80%) effectively controlled fungal growth (*Aspergillus flavus*) during the postharvest storage of peppers (Zakari et al., 2016).

In two independent studies, *Moringa oleifera* and *V. amygdalina* were both found to suppress fungal growth during postharvest tomato storage. However, *V. amygdalina* appeared to be more effective in both cases (Yusoff et al., 2021; Tukur et al., 2021). It is important to note that the methods of crude extract preparation and the concentrations applied differed between the studies, which could influence the outcomes. Efforts to develop bio fungicide formulations from *V. amygdalina* are underway due to its potent antifungal properties (Yusoff et al., 2021).

Vernonia amygdalina (Asteraceae), commonly referred to as a bitter leaf in West Africa, is widely used in traditional dishes and has long been recognized for its medicinal properties. Its popularity has grown globally, particularly in the pharmaceutical industry of developed countries. The plant's bioactivity is attributed to its diverse sesquiterpene lactones, including vernolide, vernolepin, vernodalin, and hydroxyvernolide. These compounds are known for their potent antifungal and insect antifeedant properties (Erasto et al., 2006). This growing interest in *V. amygdalina* highlights its potential not only as a natural preservative for fruits and vegetables but also as a source of bioactive compounds for broader applications in sustainable agriculture and pharmaceutical development.

Conclusion

Several phytochemicals in plants have demonstrated significant potential for positively influencing crops at various stages of their life cycle. These compounds can help break seed dormancy, control seed-borne diseases, stimulate plant growth, enhance productivity, improve nutritional composition, and extend the shelf life of fruits by inhibiting pathogen growth. The use of plant extracts as biocontrol agents provides an eco-friendly alternative to synthetic chemicals, reducing environmental risks and human toxicity, which contributes to a more sustainable agricultural system.

Interestingly, extracts from the same plant, such as neem, moringa, and garlic, can be applied at various stages of production, offering a range of benefits if cost-effective and efficient techniques are developed for their formulation into commercially viable products. However, challenges remain in standardizing the extraction methods and application techniques, as well as identifying the active compounds responsible for these effects. Variability in results can undermine farmers' trust in plant extracts, and this is often a barrier to widespread adoption.

To overcome these challenges, a collaborative effort focused on refining information—such as optimizing extraction methods, selecting appropriate solvents, and accurately identifying active compounds—may help facilitate large-scale production and commercialization. Additionally, while many plants with known agricultural benefits are already heavily utilized in other industries, such as food formulations, using these plants for crop production may increase costs and reduce availability for consumers. Therefore, there is a strong case for exploring new sources of phytochemicals that can positively impact crop production, reducing dependency on commonly used plants.

For postharvest use, attention should also be paid to the sensory characteristics of the treated produce, as it would be inappropriate to market products with undesirable flavours or textures. Ensuring that plant extracts not only preserve crops but also maintain or enhance their quality and palatability is essential for consumer acceptance and broader market success.

Acknowledgements

We would like to thank the Agricultural Research Council (ARC)-Roodeplaat Vegetable and Ornamental Plants for providing the facilities.

Author contributions

Conceptualization, HF-M and SOA; writing—original draft preparation, HF-M; writing—review and editing, SNM, MMM, SZT. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded South Africa National Research Foundation (NRF).

Conflict of Interest

The authors indicate no conflict of interest in this work.

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