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Review

Allelopathic Effects of *Moringa oleifera* Lam. on Cultivated and Non-Cultivated Plants: Implications for Crop Productivity and Sustainable Agriculture

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Abstract

Moringa (*Moringa oleifera* Lam.) is widely recognised as a multipurpose crop suitable for human and animal consumption, medicinal, and industrial purposes, making it attractive for introduction into new ranges. Its extracts have been found to have beneficial impacts on various crop species and biological activity against multiple weeds, making their use in agriculture promising. However, concerns have also been raised about moringa's potential to negatively impact the growth and development of other cultivated and non-cultivated plant species, especially in areas where it has been introduced outside its native range. To understand the positive and negative interactions between moringa and other plants, it is essential to investigate its allelopathic potential. Allelopathy is a biological activity by which one plant species produces and releases chemical compounds that influence the reproduction, growth, survival, or behaviour of other plants with either beneficial or detrimental effects on the receiver. Plants produce and release allelochemicals by leaching, volatilisation, or through root exudation. These biochemical compounds can affect critical biological processes such as seed germination, root and shoot elongation, photosynthesis, enzymatic activities, and hormonal balance in neighboring plants. Therefore, allelopathy is an important driver of plant composition and ecological interactions in an ecosystem. This review explores the positive and negative allelopathic effects of moringa extracts on other plant species, which may help to inform decisions regarding its introduction into new biogeographical regions and incorporation into existing farming systems, as well as the use of moringa plant extracts in agriculture.

Keywords: allelochemicals; biostimulants; hormesis; inhibition; plant competition; productivity

Academic Editor: Rosilda Mara Mussury

Received: 23 May 2025
Revised: 11 July 2025
Accepted: 14 July 2025
Published: 23 July 2025

Citation: Kamanga, B.M.; Cartmill, D.L.; McGill, C.; Clavijo McCormick, A. Allelopathic Effects of *Moringa oleifera* Lam. on Cultivated and Non-Cultivated Plants: Implications for Crop Productivity and Sustainable Agriculture. *Agronomy* **2025**, *15*, 1766. https://doi.org/10.3390/agronomy15081766

1. Introduction

Moringa oleifera Lam., "moringa", is an introduced plant species in most parts of the world and currently cultivated in various tropical and sub-tropical countries due to its health and nutritional benefits [1]. Moringa can grow in and adapt to different climatic conditions, making it convenient for cultivation in various biogeographical regions, supporting its worldwide expansion and distribution. Nevertheless, there are concerns about the species becoming invasive when introduced in other areas outside its natural range [2–5]. Of particular interest is its allelopathic potential on native and other cultivated species, i.e., its ability to emit allelochemicals that can promote or inhibit the germination, growth, and establishment of other plants in proximity [6,7].

Allelochemicals are secondary metabolites that play vital roles for plant communication, competition, and protection or promote tolerance against biotic and abiotic stress [8]. These include different classes of compounds such as phenols, terpenoids, alkaloids, and flavonoids [9,10]. They are produced and emitted or released into the environment as fluids or gasses through root exudation, leaching, and volatilisation [11,12]. Plant allelochemicals influence the germination and growth of neighboring plant species by positively or negatively affecting key biological processes, including cell division, hormonal balance, photosynthesis, and enzymatic activity [13]. Hence, allelopathy is considered a critical driver of plant species composition and distribution in terrestrial ecosystems [14,15].

While plant allelochemicals can improve germination and growth, they can also exert inhibitory effects depending on concentration levels, target species, environmental conditions, and the specific target plant organs, e.g., seeds, leaves or roots [15–18]. For instance, bioactive compounds released by invasive plants can adversely affect native plants, aligning with the "new weapon hypothesis" which proposes that exotic species acquire a competitive advantage in new ecosystems because native plants, without a shared coevolutionary history, are more vulnerable to the negative effects of the novel bioactive compounds of exotic plants [19]. Although the evidence supports this hypothesis, it also indicates that responses vary among receiving plants and are influenced by allelochemical concentration [20].

Moringa plant extracts (MPE) are often used to investigate how allelochemicals affect the growth and development of other plants. Results have demonstrated that both positive and negative impacts exist [2,21]. This dual allelopathic effect of moringa must be taken into consideration before introducing the plant into new environments especially when integrating it into an existing farming system, a new ecological range, or considering its use in cropping systems through extract-based interventions. This review consolidates current knowledge of moringa allelopathy by focusing on the impacts of moringa allelochemicals on various cultivated and non-cultivated plant species. It further seeks to identify knowledge gaps for future research.

2. Review Methodology and Literature Search

A thorough information search was performed for the pertinent scientific literature on allelopathy and moringa plant species across scientific databases including Springer (https://www.springer.com/gp/life-sciences accessed on 23 May 2025), Google Scholar (https://scholar.google.com/ accessed on 15 April 2025), PubMed (https://pubmed.ncbi.nlm.nih.gov/ accessed on 3 January 2025) and Scopus (https://www.scopus.com/home.uri accessed on 18 March 2025). The search utilised terms "moringa" and "allelopathy" in conjunction with key concepts or phrases "phytochemistry," "bioactive," and "allelochemicals" to encompass the scope of contemporary research on allelochemical or biological activities and its applications. A total of one hundred and fourteen (114) published research articles were used for this review, of which sixty-six (66) offered direct and indirect information on the effects of MPE, and forty-five (46) were supported articles on the roles, mechanisms, regulation, and behaviour of allelochemicals. Two (2) additional papers [22,23] tackled the methodology for the literature search. The literature search concentrated on studies published in the past two decades, with article suitability assessed through the review of titles and abstracts, a method recognised for its efficiency in identifying pertinent research publications [22,23].

A systematic and narrative literature review was conducted to answer the following question: What are the positive and negative effects of moringa allelochemicals on the growth and development of different cultivated and non-cultivated plants? Although we are aware of the multiple pathways through which moringa allelochemicals can come into contact with target plants (through direct root exudation, leaching or volatilisation), most of the available literature focused on the application of plant extracts, highlighting the need for field studies to test moringa allelochemicals under natural conditions (Figure 1). Therefore, this review summarizes findings related to moringa plant extract applications in cereals, legumes, vegetable and fruit crops. We selected these crops because they exemplify a variety of botanical groups and represent an important share of agricultural production systems.

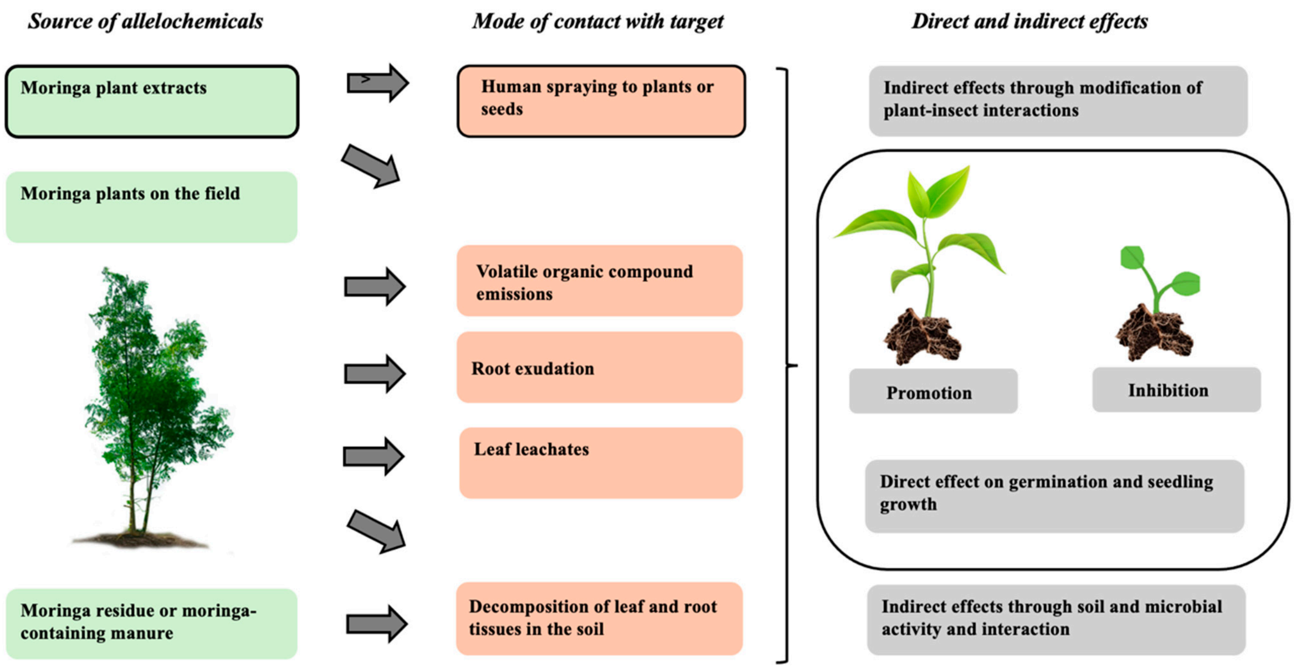

Figure 1. Different pathways through which moringa allelochemicals can reach a target plant and potential effects on the receiving plants. The boxes with black borders are the focus of this review; the other areas require further research.

3. Mechanisms Behind Allelopathic Effects

Various mechanisms by which allelochemicals directly affect target plants have been thoroughly reviewed elsewhere, so they will not be covered here in detail [24]. These include modifying the cellular structure, influencing cell division and elongation, affecting the antioxidant system or cell permeability, and altering metabolic processes (such as photosynthesis and respiration) and regulatory systems (including several hormones and enzymes).

The action of allelochemicals depends on their chemical identity, concentration, and the sensitivity of the recipient species. Typically, exposure to a low dose can induce a beneficial adaptive response in target plants, while higher doses may have detrimental effects. This phenomenon is known as hormesis [17,25]. However, different plants may vary in their sensitivity. For instance, as mentioned earlier, native plants may be more sensitive to allelochemicals of exotic plants they did not co-evolve with [19].

There are a variety of compounds involved in negative allelopathy including terpenoids, phenolics, quinones, and nitrogen-containing compounds. At sufficient concentrations, monoterpenes such as eucalyptol, camphor and citral, can induce cellular abnormalities in the nucleus, cell wall and other organelles such as vacuoles and microtubules. Other monoterpenoids (e.g., camphor, 1,8-cineole, β-pinene, α-pinene, and camphene) have been reported to affect cell division and DNA synthesis in plant meristems [26]. Quinones and phenolics are commonly reported to enhance the production of Reactive Oxygen Species (ROS) or interfere with antioxidant activities in the receiving plants. This imbalance causes degradation of molecules such as proteins, ultimately leading to apoptosis or necrosis [27]. Other phenolics such as chlorogenic acid, caffeic acid, and catechol inhibit enzymes involved in seed germination (e.g., λ-phosphorylase), while salicylic acid inhibits the synthesis of the plant hormone ethylene [16]. Benzoquinones such as sorgoleone, can impact photosynthesis by affecting the normal function of the photosystem II (PS II), a crucial protein–pigment complex involved in the light-dependent reactions of photosynthesis [28]. Nitrogen-containing compounds such as cyanogenic glycosides, can release hydrogen cyanide, which inhibits cellular respiration by blocking the enzyme cytochrome c oxidase disrupting electron flow [24].

While at higher concentrations, allelochemicals affect cellular structure and impede vital activities that result in the inhibition of germination and seedling growth in sensitive plants, stimulatory allelopathic effects including enhancement of seed germination and seedling growth are often observed at lower concentrations [17,25]. At lower concentrations, most allelochemicals such as phenolics and flavonoids facilitate antioxidant enzyme activities like superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX), that improve and maintain the cell's redox equilibrium and resistance to abiotic stress [18,25]. Additionally, some vitamins such as vitamin C (ascorbic acid), and plant hormones including auxins or cytokinins can facilitate prolific cell division, shoot and root growth, and photosynthetic activities for rapid plant growth and increase productivity [18,29]. Some examples of compounds with stimulatory and inhibitory activities found in moringa plants are summarized in Table 1.

Table 1. Chemical and antioxidant constituents identified in moringa plant extracts and their roles in allelopathy.

Compound Class	Key Compounds	Biological Role	Allelopathic Potential	Ref.
Phenolic acids	Chlorogenic, gallic, ferulic, tannic acids, and coumarins.	Antioxidant, allelopathic, signaling molecules.	Stimulatory at low dose (growth promoter); root induction; inhibitory at high doses (inhibit growth).	[30,31]
Flavonoids	Quercetin, kaempferol, rutin, naringenin.	ROS scavenging, UV protection, auxin transport molecules.	Variable; function as growth enhancers or inhibitors of competing species via ROS modulation.	[30]
Glucosinolates/ Isothiocyanates	Benzyl glucosinolate/isothiocyanate.	Allelopathic, detoxifying enzyme induction.	Suppression of seed germination/DNA alkylation, enzyme inhibition.	[32,33]
Tannins	Catechin, epicatechin.	Defense compounds, metal chelators.	Inhibitory effect: interfere with nutrient uptake and enzyme activity.	[16]
Alkaloids	Moringine, moringinine.	Modulation of stress response, antimicrobial.	Allelopathic inhibition: affect cell division and germination in sensitive species.	[33]
Saponins	Triterpenoid saponin.	Antimicrobial, membrane interaction.	Inhibit growth in some plant species.	[34]
Amino acids	Arginine, proline, glutamic acids.	Growth regulators, hormone precursors, osmoprotectants.	Stimulatory effect: promote resilience in intercropping species via root exudation.	[35,36]
Minerals	Fe, Zn, Ca, Mg, K, Mn, B.	Enzyme cofactors, chlorophyll structure, osmoregulation.	Indirect allelopathy through soil nutrient alteration (enhance or inhibit growth).	[21,37]
Hormones (Cytokinin)	Zeatin and its derivatives, gibberellins.	Promote cell division, shoot development.	Positive allelopathy: promotes growth of plants in proximity.	[38,39]
Vitamins (antioxidants)	Ascorbic acid (vit. C), α-tocopherol, β-carotene.	Maintain redox balance, protect membrane and enzymes.	Stimulatory to receiving plants through oxidative stress reduction.	[40,41]

4. Moringa Plant Extracts as Biostimulants

Moringa leaves, roots, seeds, and bark contain a broad spectrum of phytochemicals capable of altering plant physiology, metabolism, hormonal balance, and gene expression that influence receiver plant's productivity. Mineral nutrients [42], phenolics and flavonoids [43], and other numerous bioactive compounds [29,44], make MPE unique in nature. MPE contains phytohormones such as gibberellin, auxin, and cytokinin [45,46], which are known to affect different parts of plant growth and development [18]. Moringa extracts contain important nutrients, such as nitrogen, phosphorus, potassium, calcium, magnesium, and other trace elements, i.e., copper, iron, zinc, and manganese. These nutrients are vital for the plant metabolism, structure, and function of different plant cells [46,47]. The plant contains proteins, amino acids, and vitamins, which play important roles in growth, enzyme function and metabolism, stress tolerance, and overall plant health [48,49].

Moringa has phenolic and flavonoid compounds that function as antioxidants. These support the plant to defend against biotic and abiotic stress factors in their environment [50–52]. The plant has saponins which aid several biological activities and could help to maintain plant health and protect against pests and diseases [53]. Previous studies assessed and evaluated moringa leaf extracts (MLE) for bioactive compounds and found zeatin, and its derivatives of plant cytokinin. These substances have beneficial effects on plants, similar to synthetic hormones that promote growth in plants [54]. When phytohormones are applied to plants, they induce positive effect on numerous plant physiological and biochemical processes such as the ascorbate glutathione cycle, transpiration rates, cell division, nitrogen metabolism, and assimilation activities that promote plant growth and yield enhancement [55].

Moringa leaf extracts are known and recognised as an alternative option among biostimulants available because of their numerous bioactive compounds that promote plant growth and their ability to enhance soil nutrients when utilised as green manure [56,57]. Research has shown that aqueous moringa plant extracts (Aq. MPE) promote growth and productivity of various crops (Table 2). However, plants respond differently to varying concentrations, with higher application rates exerting inhibitory effects on certain crops [58]. Thus, it is important to understand the biochemical and physiological processes of receiving plants to successfully use natural biostimulants from plant extracts. Table 2 shows the concentration rates and the positive allelopathic effects of MPE on the growth and development of different agricultural crops.

Table 2. Stimulatory effects of moringa plant extracts on the growth and development of crop species.

Source	Concentration	Observed Effects and Target Crop	Ref.
		Cereal Crops	
Aq. MLE	4:1, 3, 25% (*v*/*v*)	Improve growth, yield, and stress tolerance in maize (*Zea mays*).	[31,56,59]
Aq. MLE	3% (*w*/*v*)	Improve growth, yield, and photosynthetic activities in wheat (*Triticum aestivum*).	[60,61]
Aq. MLE	100% (*v*/*v*)	Improved growth parameters on sorghum (*Sorghum bicolor*).	[62]
Aq. MLE	3% (*v*/*v*)	Enhanced physiological, biochemical, and yield parameters rice (*Oryza sativa*).	[63]
		Leguminous Crops	
Aq. MLE	1:30 (*w*/*v*)	Accelerated growth of cowpeas (*Vigna unguiculata*).	[64]
Aq. MLE	1:20 (*w*/*v*)	Speeded and supported an antioxidant system and tolerance under stress in common/snap beans (*Phaseolus vulgaris*).	[38]
Aq. MLE	1, 2, 3, and 4%	Increased yield and nutrient in pea plants (*Pisum sativum*) and mustard spinach (*Brassica rapa* var. perviridis).	[41]

Table 2. *Cont.*

Source	Concentration	Observed Effects and Target Crop	Ref.
		Vegetable Crops	
Aq. WPE	10% (*w*/*v*)	Improved growth parameters and yield of spinach (*Basella alba*) and tomatoes (*Solanum lycopersicum*).	[65]
Aq. MLE	1:30 (*w*/*v*)	Enhanced growth, fruit weight, and nutrient contents of eggplant/brinjal (*Solanum melongen*).	[66]
Aq. MLE	10% (*v*/*v*)	Influenced growth, photosynthetic activity, and nutrient absorption in cabbage (*Brassica oleracea* var. capitata).	[67]
Aq./Ethanol MLE	1:10 (*v*/*v*)	Influenced vegetative growth and increased yield components in sweet pepper (*Capsicum annum* var. annum).	[68,69]
Aq. MLE	1:20 (*w*/*v*)	Enhanced the growth and development of cucumber (*Cucumis sativum*).	[35]
		Fruit Crops	
Aq. MLE	3% (*w*/*v*)	Improved yield and nutrient contents of kinnow mandarin (*Citrus nobilis* × *Citrus deliciosa*).	[70]
Aq. MLE	6% (*w*/*v*)	Enhanced fruit weight and anthocyanin strawberry fruits (*Fragaria* × *ananassa*) and plums (*Prunus domestica*).	[71]
Aq. MLE	3.5% (*v*/*v*)	Improved quality and nutritional contents of grapevine (*Vitis vinifera*).	[72]
		Other Cultivated Plants	
Aq. MLE	3% (*w*/*v*)	Improved growth, biochemical attributes of quinoa (*Chenopodium quinoa*).	[73]
Aq. MLE	50% (*w*/*v*)	Increased the yield and the yield components sunflower (*Helianthus annuus*).	[74]
Aq. MLE	100% (*v*/*v*)	Promoted growth of nut sedge (*Cyperus rotundus*).	[75]
Aq. MLE	30% (*w*/*v*)	Enhancing seed germination and seedling vigour of barnyard grass (*Echinochloa crusgalli*), buffel-grass (*Cenchrus ciliaris*), and blue panic grass (*Panicum antidotale*).	[76]
Ethanol MSE	2,4, 6, 8% (*v*/*v*)	Improved growth and nutrient contents in cancer bush (*Lessertia frutescens*).	[21]

MLE = moringa leaf extracts, WPE = whole-plant extracts, MSE = moringa seed extracts, Aq. = aqueous extracts, and ethanol = ethanolic extracts.

4.1. In Cereals

Moringa extracts exhibit concentration-dependent effects on key physiological parameters in cultivated cereal crops including seed germination, root and shoot length, and promote photosynthetic activity [17]. For example, exogenous application of MLE at the rate of 25, 12.5, 6.25, 3.13, and 1.56% improve seedling growth, soluble leaf proteins, and leaf relative water content in maize under drought stress [31], while 25% (*w*/*v*) of Aq. MLE improved germination and seedling growth of the same crop [54]. Furthermore, foliar application of Aq. MLE improved growth, grain, and biomass yield under field conditions [77], while applying Aq. MLE two weeks after emergence and four weeks later increased plant height, fresh and dry shoot biomass, and yield of the same crop [78]. Maize seed priming with Aq. MLE improved antioxidant activities (CAT and POD) by 22–56% that reduced hydrogen peroxide production. Additionally, a 3% (*v*/*v*) application of Aq. MLE resulted in hermetic effect in elevating salinity stress thereby improving germination, growth, photosynthesis, and antioxidant activities [59]. The analysis of moringa extracts found numerous plant growth hormones including gibberellins (GA_4) and indole acetic acid (IAA) that have been reported to enhance growth in different cereal crops [79]. Moreover, GA_4 stimulates and facilitates the formation of hydrolytic enzymes such as amylase, which breaks down the reserved food substances held in seed endosperm into simple sugars to provide energy for germination and seedling growth [80].

Wheat crop responded positively to the application of fresh Aq. MLE at the rate of 3% (*w*/*v*) and significantly improved seedling growth, productivity, and grain yield under drought stress conditions [60]. It further increased the contents of chlorophylls a and b when applied at tillering and heading stages [61]. Although research has demonstrated a hormesis response to MLE [17], spraying a 100% concentration of Aq. MLE improved growth parameters in sorghum, the results were attributed to the availability of zeatin, a natural substance used as a source of cytokinins along with other minerals and phytohormones that balance physiological and biochemical processes to enhance growth and yield of crops when applied exogenously [62].

Drought stress negatively affects physiological, biochemical, and yield parameters of various crops. It affects gas exchange attributes, antioxidant enzymes' activities, photosynthetic efficiency, yield, and yield components of rice [63]. However, foliar application (3%) of Aq. MLE improved gas exchange traits, photosynthetic pigments, seedling establishment, growth, and yield of the same crop under normal and drought stress conditions [63]. Biochemical improvements in SOD, CAT, and APX in rice provide evidence for the presence of antioxidants that protect the plant from oxidative damage [36]. Additionally, MLEs function as exogenous growth enhancers due to the presence of zeatin, carotenoids, ascorbate, antioxidants, essential plant nutrients, and vitamins [81,82]. These improves endogenous hormonal balance during stress to improve overall plant growth, yield and yield components [82].

Similarly, MLE were effective in improving growth and productivity of cereal forages (millet, pearl millet, and Sudan grass) under salinity stress environment. A 1 mL^{-1} 10 mL of Aq. MLE contained the highest concentration of inorganic elements and growth hormones (cytokinin, auxin, gibberellins, and abscisic acid), these contributed to an increased fresh and dry forage yield by 17.67 and 4.87%, respectively [83]. The analysis of MLE found rich contents of zeatin, a cytokinins which sustain the green colouring matter for photosynthetic activity that supports continued growth, accumulation of biomass, and higher grain yield under drought and salinity stress [83]. It is reported that the role of plant hormones in MPE is to regulate and maintain photosynthetic activity by protracting senescence and modify plant phenotypic response towards harsh environment. The presence of zeatin and its derivatives could explain the rapid germination and growth in different cereal species under abiotic stress.

4.2. In Leguminous Plants

Studies have demonstrated that low concentration of Aq. moringa extracts from young leaves diluted with water had stimulatory effects on seed germination and seedling vigour of leguminous crops including mung bean, cowpeas, snap beans, and chickpea [38,41,45,84]. MPE's antioxidants play essential roles in reducing or alleviating oxidative damage thereby enhancing plant growth and productivity under stress environments [52]. Low concentration rate of 1:30 (*w*/*v*) at 25 mL per plant accelerated stem growth, increased the number of leaves, and branches in the range of 10–45% in cowpeas [64]. While a ratio of 1:20 (*w*/*v*) of MLE sprayed on 30 and 37 days after sowing speeded and supported an antioxidant system and tolerance under varied levels of salt stress thereby improving growth and yield in common/snap beans [38]. Further, lower concentration rates of 1, 2, 3, and 4% significantly increased fresh pods yield, biological yield, protein content, and nutrient accumulation in pea plants; however, high protein content and photosynthetic activities were obtained at 4% concentration [41]. The analysis of MLE found a higher concentration of GA_4 than other hormones.

Enhanced growth, yield, and yield components in legumes following the application of MLE has been linked to the availability of phytohormones and antioxidants [45]. It can be suggested that stimulatory effects of MLE on different legumes is due to the presence of natural zeatin, ascorbic acid, and quercetin, which enhances cell division, maintain membrane integrity, and modulate redox signaling pathways during optimal and suboptimal conditions. Antioxidants eliminate harmful free radicals and reduce oxidative stress that helps to protect plant cells from damage [85]. Phytohormones further synergistically upregulate photosynthesis-related genes and antioxidants enzyme activity including SOD, CAT, and APX which enhance chlorophyll biosynthesis, carbon assimilation, and stress tolerance in legumes thereby promoting plant productivity [41]. Protection allows plants to maintain their physiological functions and optimize nutrient uptake under salinity, thus improving photosynthetic efficiency, overall growth, vigour, and plant health [39,41,54].

4.3. In Vegetable Crops

Although certain phytohormones possess similar effects in different plant species, research suggests that the specific response varies due to differences in plant physiological, hormonal receptors, interactions, environmental niche, hormone transport and distribution patterns, and genetic variation among plants [86]. For example, spraying low concentration of MLE 1:10 (*w*/*v*) fortnightly (Aq. 25 mL per plant) improved growth parameters by 25% and increased yield in tomatoes and malabar spinach [65]. However, the effects on spinach were slightly lower than those of tomatoes, providing further evidence that various crop species respond differently to allelochemicals. Furthermore, the application of Aq. MLE at the ratio of 1:30 (*w*/*v*) enhanced growth, fruit weight, and nutrient contents such as nitrogen, potassium, and phosphorus in egg plants [66]. It can be hypothesized that the presence of zeatin, GA_4, ABA, IAA and salicylic acid (SA) in MLE, each with distinct roles in regulating plant growth and development. Zeatin promotes cell division and lateral bud growth. Gibberellin, a plat hormone involved in stem elongation, seed germination, and flowering, ABA primarily regulates seed dormancy, stress responses by closing stomatal, and senescence, whereas IAA, an auxin, influences cell elongation, apical dominance, and root development. In turn, all these facilitate rapid growth, biomass accumulation, and crop yield [45].

Application of 10% (*v*/*v*) concentration of Aq. MLE at a rate of 25 mL per plant positively influenced growth, photosynthetic pigments (anthocyanins), nutrient absorption, and reduced nitrate content by 12% in cabbage [67]. Interestingly, applying a reduced concentration rate of 6% resulted in an even greater reduction in the nitrate content by 23%, contrasting previous findings that higher concentrations have detrimental effects on plant growth and development [17]. This signifies a differential response of plant species to bioactive compounds [16]. Similarly, foliar application of ethanolic MLE (20 g with 675 mL of 80% aq. ethanol) in the ratio of 1:10 (*v*/*v*) positively influenced vegetative growth and increased sweet pepper yield components by 1.68 kg per plant and 16.88 tons per hectare and a concentration of 4% significantly increased plant growth parameters and chemical composition of the same crop [68,69].

A ratio of 1:20 (*w*/*v*) of Aq. MLE promoted the growth and development of cucumber fruits (fruit fresh and dry weights, and total fruit yield) and increased endogenous hormone levels (auxins, gibberellins, and cytokinins); and also promoted the activity of the antioxidant enzymes superoxide dismutase, catalase, and ascorbate peroxidase in cucumber leaves [35].

4.4. In Fruit Crops

Several studies have shown that moringa plant extracts positively influence fruit crops through the enhancement in fruit quality, increasing fruit shelf life, and promoting resistance to pests and diseases. For instance, applying Aq. MLE to the leaves at the rate of 3% (*w*/*v*) improved kinnow (mandarin) fruit size and weight, sweet, and increased the content of phenolic and ascorbic acids [70] while application of a 6% (*w*/*v*) concentration of MLE enhanced fruit weight and anthocyanin levels in strawberries and enhanced firmness and colour traits in plums [71,87]. Foliar application of Aq. MLE at 3.5% (*v* /*v*) improved firmness, fruit diameter, and titratable acidity in grapevine fruits [72]. The enhancements in fruit quality and its associated nutrient composition are due to the presence of essential nutrients in MLE that influence plant metabolism by augmenting the synthesis of vitamin C and other trace elements in leaves, thereby facilitating their transport to the fruit through the phloem [70].

4.5. In Other Cultivated Plant Species

Folia application of Aq. MLE at the concentration rate of 3% (*w*/*v*) enhanced the physiological and biochemical responses, quality attributes, as well as growth and yield components of quinoa. It further increased the activities of antioxidant enzymes including SOD, CAT, and APX along with elevated levels of total phenolics and glycine betaine. The concentration of key mineral nutrients including K, Ca, and N was found to be highest in root and shoots in response to MLE [73]. Other studies have shown that the application of Aq. MLE and moringa root extracts (MRE) at 50% (*w*/*v*) significantly increased the yield and the yield components of common sunflower including the number of achenes per plant [74]. Aq. MSE at the concentration rates of 2, 4, 6, and 8% increased growth characteristics, chlorophyll content, phenols, and flavonoids contents in cancer bush plants; however, 6 and 8% concentrations were highly effective. It further enhanced the concentration of micronutrients including zinc, copper, manganese, and sodium of the same plant.

Although research has demonstrated the hormesis phenomenon in plants [25,88], application of Aq. MLE at 100% (*v*/*v*) concentration significantly enhanced both fresh and dry biomass weight of the shoots, as well as the shoot and root lengths of purple nut sedge [75]. Several grass species including barnyard grass, buffel-grass, and blue panic grass, were shown to benefit from seed priming with a 30% (*w*/*v*) MLE, which was proven to be efficient in enhancing seed germination and seedling vigour, crude protein, and phosphorus contents [76]. Further, maximum potassium, calcium, and magnesium contents of the same crop were found when the seeds were treated with moringa extracts. The effectiveness of MLE in promoting growth and development in various crops can be attributed to the presence of nutrients and plant growth regulation hormones, zinc, ascorbic acid, calcium, and potassium in moringa plant.

5. Moringa Plant Extracts as Plant Growth Inhibitors

The inhibitory effects of allelochemicals manifest in several ways including reduced seed germination, impaired seedling growth, nutrient uptake, suppression of photosynthetic activities by interfering with enzymatic activities and its metabolic pathways, resulting in overall decrease in productivity of infected plants [89,90]. The effect entails biochemical interactions at different growth stages that affect the processes of germination, development and productivity of adjacent plants [91]. Despite the MLE's significant concentration of phenolic acids, terpenes, and alkaloids, research has shown that the allelopathic efficacy of phenolic acids and their derivatives from plant roots are constrained by high biodegradability and strong adsorption to soil particles [92]. Hence, most studies on the allelopathic effects of moringa have concentrated more on leaf extracts than on root extracts and often conducted in controlled laboratory setups in which growth conditions mostly differ from natural environment. The negative allelopathic effects of MPE on leguminous, vegetable, fruit, and other crops are highlighted in Table 3.

Table 3. Inhibitory effects of moringa plant extracts on the growth and development of various crops.

Source	Concentration	Target Crop and Observed Effects	Ref
		Leguminous Crops	
Aq. MRE	10% (*v*/*v*)	Reduced growth parameters of mung beans (*Vigna radiata*).	[93]
Aq. MLE	5–10% (*w*/*v*)	Inhibitory effects broad beans (*Vicia faba*) and chickpea (*Cicer arietinum*).	[60,94,95]
Aq. MLE	1:10 (*w*/*v*)	Reduced germination and survival of cowpea (*Vigna unguiculata*) and groundnuts (*Arachis hypogaea*).	[84]
		Vegetable, Fruit and Other Crops	
Aq. MLE	0.45–0.90 mg·mL^{-1}	Reduced germination and seedling growth of wild mustard (*Synapsis arvensis*).	[2]
Aq. MPE	>10% (*v*/*v*)	Inhibited shoot and root length of curly/garden cress (*Lepidium sativum*).	[17]
Aq. MPE	100 (*v*/*v*)	Inhibited germination of okra (*Abelmoschus esculentus*).	[96]
Methanol MPE	0.03, 0.01, and 0.1 g·mL^{-1}	Inhibited the growth of lettuce (*Lactuca sativa*) and curly cress (*Lepidium sativum*).	[97]
Aq. MLE	25 mg·mL^{-1}	Reduce yield of eggplant (*Solanum melongena*) and sweet corn (*Zea mays*).	[98]
Aq. MLE	2.5–10% (*w*/*v*)	Suppression of germination and growth of watermelon (*Citrullus lanatus*).	[99]
Ethanol MLE	20–25 g·mL^{-1}	Inhibited germination and growth of tomatoes (*Solanum lycopersicum*).	[3]

MLE = moringa leaf extracts, MRE = moringa root extracts, Aq. = aqueous extracts, ethanol = ethanolic extracts, and methanol = methanolic extracts.

5.1. In Leguminous Plants

The effect of MPE has been described as hormesis [17] i.e., higher concentrations exhibit growth inhibitory effect by reducing seed germination, early seedling growth, and chlorophyll degradation in several cultivated and non-cultivated plants [32]. Although MLE have shown some positive allelopathic effects in various legume crops, MRE (Aq. water extracts) applied at the higher concentration rate of 10% (*v*/*v*) had detrimental effects on mung beans germination, shoot and root growth, resulting in total reduction in dry matter biomass, number of pods, and yield per plant by 40%, 41%, and 43%, respectively [93]. The differential effects observed between MLE and MRE in stimulating growth and development of mung beans demonstrate that various parts of the moringa plant may possess distinctive bioactive compounds that render differential physiological and biochemical functions in other plants.

Higher concentration rates of 5% and 10% (Aq. MLE *w*/*v*) had inhibitory effects on broad beans and chickpea, respectively. They reduced seed germination, seedling growth, biomass accumulation, and biochemical components by more than 50%, and recommended that all moringa plants should be rogued out before sowing broad beans and chickpea [60,94,95]. The same authors reported the decreased efficiency in photosynthetic pigments and chlorophyll fluorescence spectra with greater effect on broad beans. Inhibition of growth in recipient plants is associated with oxidative burst caused by phenolic acid overaccumulation that leads to the disruption of cellular respiration and auxin transport system. Damage of cell membranes affects the entire metabolism and physiological process which affects intermembrane ion transport, accumulation and water imbalance, causing malfunction of cellular activities and eventually inhibit plant growth [100].

Aqueous MPE at the ratio of 1:10 (*w*/*v*) had an inhibitory effect on germination and survival of groundnuts and cowpeas [84]. It lowered the survival rate of cowpeas by 4% and groundnuts by 10%. It also reduced radicle length by 24% and 21% in cowpeas and groundnuts, respectively. Furthermore, the extracts reduced the development of seed hypocotyls by 4% in cowpeas and 66% in groundnuts. Research has shown that MPE contains benzyl isothiocyanate and ferulic acid which impede mitotic activity in apical meristem and disrupts rhizosphere microbial dynamics. This reduces the nodulation and nitrogen fixation capacity in legumes and eventually affects their growth and productivity [101,102].

5.2. In Vegetable, Fruit and Other Crops

Allelochemicals affect distinct stages of plant growth and development in diverse ways. Some allelochemicals interfere with enzyme activities and other processes that occur during the initial stages of seed germination. For instance, (-)-catechin, a secondary chemical compound in moringa leaves, impeded enzymes activity including amylase and protease, hindering the mobilization of nutrients essential for germination and seedling growth [103]. Applying 0.90 mg·mL^{-1} of MLE during sowing reduced the number of seeds germinated and seedling growth of wild mustard than applying 0.45 mg·mL^{-1} [2], indication a concentration-dependent allelopathic activity.

Allelochemicals, such as caffeic acid, disrupt physiological functions and the balance of plant regulatory hormones involved in seed germination including ABA, GA_4, and auxins [104,105]. These allelochemicals enhance the effects of ABA, a hormone that suppresses germination, by interfering with the signaling pathways and biosynthesis of GA_4 (which promote seed germination) [80].

Aqueous MPE (>10% *v*/*v*) inhibited shoot and root length of garden cress by 38% and 85%, respectively [17]. Metabolite analysis and profiling of MLE identified twelve compounds associated with allelopathic effect including p-coumaric acid, salicylic acid, p-hydroxybenzoic acid, p-hydroxybenzaldehyde, and gallic acids which have strong allelopathic effect, i.e., inhibit seed germination and seedling growth of various plant species [44,106,107]. The bioactive compounds were further analysed in the leaves, seeds, and flowers of moringa, the results showed that MLE were rich in methyl 11,14,17-eicosatrienoate (13.69%) and octadec-9-enoic acid (27.8%); flower extracts were rich in nonacosane (18.3%), methyl 12, 15-octadecadienoate (17.9%), and 9-octadecenoic acid methyl ester (36.9%); and root extracts were rich in (*E*)- 9-octadecenoic acid, methyl ester (36.94%) and octadec-9-enoic acid (16.66%) [2].

These chemical compounds enhance the permeability of the cellular membrane, resulting in damage to the protein membranes and their channels. This disrupts the transportation of nutrients to different parts of the plant, which in turn affects its metabolic activity [24]. The damaged membranes hinder energy production pathways, decreasing growth and productivity in the majority of plants, specifically biomass accumulation [32]. The allelochemical compounds and their respective quantities present in moringa could have exerted an inhibitory effect on the growth, yield, and yield components of garden cress.

Higher concentration of moringa leaf, seed, and flower extracts had a strong bioactive effect on various vegetable crops. For instance, 100% Aq. MLE caused maximum inhibition with (0%) germination, mean germination time, and shoot length of okra [96]. Similarly, 20–25 g·mL^{-1} alcohol MLE was found to be toxic against germination and seedling growth of tomatoes plants [3]. Some plants deploy advanced mechanisms to counteract harmful toxins or varied amounts of allelochemicals, while other plants are more susceptible to toxin concentrations emitted by donor plants in the soil. The observed germination and growth disorders in these crops can be attributed to allelochemical activity that induce physiological and biochemical malfunction, and hormonal imbalances in different plant species [20].

Methanol extracts of whole moringa plants at different concentrations, i.e., 0.03, 0.01, and 0.1 g·mL^{-1} had inhibitory effects on hypocotyl and root growth of curly cress and lettuce with concentrations more than 0.03 mL^{-1} exacerbated the effect to 100% [97]. The presence of coumarin and cinnamic acids, coupled with other phenolic chemical compounds in moringa might have caused the inhibitory action. These organic acids compromise and hinder seeds from germinating [92]. They further cause oxidative stress in seeds and seedlings by making ROS, and the accumulation of ROS deters the function of proteins, lipids, and DNA in cells, thereby damaging and compromising seed viability, germination, and seedling growth [108].

Moringa has been described as extremely competitive with eggplant and sweet corn varieties with a reduction in yields by more than 50% [98]. A 25 $mg \cdot mL^{-1}$ concentration of Aq. MLE inhibited the growth of eggplant seedlings, demonstrating the availability of compounds responsible for growth suppression [3]. Suppression of seed germination, plumule, and radicle elongation were visible seven days after spraying Aq. MLE in watermelon at the concentration rate between 2.5 and 10% (w/v) [99]. Harmful allelochemicals and light blocking are suggested to compromise and causes breakage in membrane which in turn slow down germination and seedling growth. Plant cell membranes play important roles in keeping the balance of water and nutrients and controlling the transport of molecules in plants [109]. Allelochemicals break down cell membrane during initial stages of seedlings growth, causing leakage of cellular contents, this leads to the loss in cell integrity. This phenomenon compromises important physiological and biochemical processes such as osmotic regulation, ion transportation, and metabolic activities, which in turn affect seed germination, seedling growth, and the ability of plants to deal with stress factors in the environment [24].

6. Potential Allelopathic Effect of Moringa on Weeds

Weed management is one of the major concerns in sustainable crop production systems. Weeds cause significant losses in agriculture by competing with crops for essential resources including soil nutrients, light, water, and air. This has prompted farmers to use synthetic herbicides to control weed species. However, continued and heavy herbicide usage raises concerns over human health and the environment [110]. Hence, researchers and farmers have been exploring alternative environmentally friendly and effective solutions to control weeds including the use of plant extracts. Recent studies have demonstrated that some plant species possess potent allelochemicals that can be screened for potential and ecofriendly natural herbicides to control weeds [100,111]. Moringa has emerged as one of the plant species with allelopathic potential due to its diverse of secondary metabolites including phenolic acids, flavonoids, glucosinolates, and isothiocyanates [109]. Through MPE application, these have demonstrated significant bioactivity against broad range of weed species such as and lesser canary grass (*Phalaris minor*), jungle rice grass (*Echinochloa colona*), weed beet (*Beta vulgaris*), and wild poinsettia (*Euphorbia heterophylla*) [109,111].

Moringa leaf extracts have shown a strong herbicidal effect on some weed species. For instance, applying MLE at lower concentration rates suppressed seedling growth of wild poinsettia, while increasing concentration from 5 $g \cdot 100\ mL^{-1}$ to 20 $g.100\ mL^{-1}$ inhibited seed germination of the same species [111]. The results may indicate the availability of bioactive compounds with bio-herbicidal properties. Other studies have reported that a concentration of 5% (v/v) of Aq. MLE reduced the growth of both weed beet (broadleaf weed) and lesser canary grass, while at higher concentrations (>10%), it significantly reduced the growth of jungle rice grass (grassy weed) [109]. Researchers found different quantities of polyphenols and flavonoids in leaf extracts, which might have played a major role in inhibiting seedling growth [32].

Moringa water extracts used in combination with *Parthenium hystorophorus* and *Cannabis sativa* extracts (3% v/v) significantly suppressed weeds when compared to a distilled water control in a wheat-maize cropping system. This suggests that moringa extracts can be used synergistically with other plant extracts for effective weed control in agriculture. This treatment reduced leaf number, leaf length, shoot length, chlorophyll content, and photosynthetic rate in all tested weeds and the effect was linked to phenolic compounds. [103]. Regarding the potential mode of action, exogenous phenolic compounds can penetrate cell membranes and accumulate within the cell disrupting enzymatic activity, hormone signaling, antioxidant systems, respiration and photosynthetic activity among other vital plant functions [85,112].

7. Conclusions and Future Prospectives

Moringa plant extracts possess biochemical compounds that can positively and negatively influence the growth and development of various crops and weed species. Based on the findings of this review, the stimulatory properties of moringa allelochemicals, such as enhanced stress tolerance and growth promotion, can be utilised or applied in the development of biofertilizers or biostimulants. Conversely, moringa's allelochemical inhibitory effects on seed germination and seedling growth can be harnessed for the development of bioherbicides for sustainable weed management. Despite moringa allelochemicals possessing dual allelopathic roles, there is a lack of research exploring the underlying physiological and molecular mechanisms. Therefore, future studies should focus on how biochemical pathways and gene expression are influenced by moringa extracts to better understand their mode of action and optimize their application in sustainable agriculture production.

We identified several gaps in the literature. For instance, there is little information on the effect of moringa allelochemicals on temperate pasture species like perennial ryegrass (*Lolium perenne*), white clover (*Trifolium repens*). Also, effects on native, endemic, ornamental, and naturalised plants that are not cultivated are poorly explored. Additionally, we found that most studies on allelopathic impacts of moringa involve leaf extracts with fewer studies exploring extracts from other parts of the plant such as bark, flowers, or roots.

Investigating the allelopathic effects of root extracts and exudates can be of particular interest given that roots are potential carriers of numerous bioactive compounds [95], and these compounds can be released into the rhizosphere influencing the growth and development of nearby species. We recommend more studies to characterise root-specific metabolites and laboratory and field trials to investigate their effects on other crops, native species and weeds, and the mechanisms behind the observed direct impacts.

The indirect impacts of moringa extracts are poorly documented, and future research should also concentrate on how moringa allelochemicals may affect other plants indirectly through changes in soil properties, plant-insect, and plant-microbe interactions. Additional research could also explore how environmental stress factors (such as drought or extreme temperatures) influence allelochemical production and activity in moringa, given that such factors are known to impact the production and release of secondary metabolites and the ecological interactions these mediate [113,114].

We have summarized key findings and identified avenues for future research; however, as the body of the literature develops, we recommend and encourage controlled trials to explore moringa's allelopathic potential to be conducted before its introduction into a new ecosystem or using its extracts on other plant species as biofertilizers or biopesticides.

Author Contributions: B.M.K. and A.C.M. developed the main idea for the manuscript and wrote the original draft. D.L.C. and C.M., as doctoral supervisors of B.M.K., provided significant input and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Massey University, New Zealand through a Massey Doctoral Scholarship.

Data Availability Statement: As this article is a literature review, no primary data were collected or generated.

Acknowledgments: The authors are grateful to the anonymous reviewers and corresponding editor for their helpful, constructive comments, and suggestions for improving the manuscript.

Conflicts of Interest: The authors declare that they have no known competing monetary interests or personal relationships that could have appeared to influence the work reported in this paper.

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