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Review

Use of Botanical Pesticides in Agriculture as an Alternative to Synthetic Pesticides

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Abstract: Pest management is being confronted with immense economic and environmental issues worldwide because of massive utilization and over-reliance on pesticides. The non-target toxicity, residual consequence, and challenging biodegradability of these synthetic pesticides have become a serious concern, which urgently requires the alternative and prompt adoption of sustainable and cost-effective pest control measures. Increasing attention in environmental safety has triggered interest in pest control approaches through eco-friendly plant-based pesticides. Botanical pesticidal constituents are effective against myriads of destructive pests and diseases. More importantly, they are widely available, inexpensive, accessible, rapidly biodegradable, and have little toxicity to beneficiary agents. The phytochemical compositions in diverse plant species are responsible for their varying mechanisms of action against pests and diseases. However, difficulties in their formulation and insufficient appropriate chemical data have led to a low level of acceptance and adoption globally. Therefore, the review seeks to highlight the status, phytochemical compositions, insecticidal mechanisms, and challenges of plant-based pesticide usage in sustainable agricultural production.

Keywords: pest management; botanical pesticides; mechanisms of action; challenges

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1. Introduction

In the era of Green Revolution technology, the 1950s and 1960s, crop production was intensified to meet food availability in low-income nations through substantial utilization of inputs such as inorganic fertilizers, synthetic pesticides, and genetically modified organisms [1,2]. About 67,000 species exhibit noticeable benefits on agricultural crops, and more than 70% of agricultural production would suffer colossal losses without proactive and preventive measures by utilizing agrochemicals [2,3]. Oftentimes, farmers prefer to adopt quick-fix pest management solutions, i.e., synthetic pesticides, to protect the crops from pest attack and damage [4]. However, the efficacious attributes and repetitive abuse of synthetic pesticides result in many bottlenecks, especially leading to pest resistance and health-related issues [5]. The indiscriminate use of these synthetic pesticides has caused unwanted consequences, such as environmental degradation, harm to non-target organisms, pesticide residues contaminating food and feed, pest resurgence, genetic variation in plants, and negative impacts on biodiversity [6,7].

The toxic effects of synthetic pesticides on human lives include but are not limited to the bioaccumulation of contaminants in food chains, which are widely spread in terrestrial and aquatic environments [8]. The most common synthetic pesticides (Dichlorodiphenyl-trichloroethane and toxaphene) could result in residual effects on the soil for decades, and they could be washed off into groundwater and aquatic biota [9]. The persistence of human illnesses, either due to ingestion or exposure, lead to adverse effects on immune systems, impairment of neurodevelopmental and endocrine systems, metabolic diseases, cancer, and infertility [10,11], and these are key health risks related to the continuous use of synthetic pesticides [12]. In several rural settlements, the quality of synthetic pesticides is often compromised by dilution, improper mixing, and sale beyond expiry dates [13]. The World Health Organization reported that 200,000 people die annually across the world due to the direct impact of pesticides [14]. Notably, a large number of synthetic pesticides persist in the environment, thereby polluting the soil as well as water bodies and depleting the ozone layer [15,16]. It is worth noting that the consumption of synthetic pesticides in Africa was about USD 31 billion, which is 2–4% of the world pesticide market [17]. However, it has been reported that Africa has the highest human fatality rate risks because of the inappropriate use of pesticides [18]. The United Nations Environmental Program reported that the cost of pesticide-related illnesses could reach USD 90 billion in Sub-Saharan Africa between 2005 and 2020 [19]. The adverse consequences related to the inappropriate and overuse of chemical pesticides have necessitated the need for alternative means of pest management [20]. Thus, there is a greater focus on the development and research of botanical pesticides.

Botanical pesticides were widely utilized for millennia in both subsistence and commercial farming before the development of synthetic pesticides. Botanical pesticide ingredients are naturally occurring chemical derivatives of plants that act as repellants, attractants, antifeedants, and growth inhibitors [20–22]. When these compounds are extracted with appropriate solvents and/or mixed with necessary pesticide adjuvants, they become botanical pesticides. Due to the potency and efficacy of synthetic pesticides upon destructive crop diseases, the application of plant-based products slowly diminished until recently, when the heavy utilization of synthetic pesticides started posing an imminent threat to environmental safety and human health [23,24]. Botanicals are gaining popularity in organic farming due to their safety profile on crop consumption, and consumers are willing to pay a premium price for organic produce [25].

Several findings have been carried out to examine the known and unexploited plant species with pesticidal properties [26,27]. Hundreds of botanical pesticidal compounds have been discovered from many plants, including wild plants and herbal medicines. Many plants of Rutaceae, Compositae, Meliaceae, Leguminosae, Araceae, Platycodoniaceae, Solanaceae, Chenopodiaceae, Zingiberaceae, Labiatae, Loniceraceae, Umbelliferae, Polygonaceae, and Euphorbiaceae possess pesticidal attributes, and numerous compounds of plant secondary metabolites, including alkaloids, terpenoids, and flavonoids that show pesticidal activities. Interestingly, some commercially plant-based pesticides are mainly extracted from pyrethrum (*Tanacetum cinerariifolium*), tobacco (*Nicotiana tabacum* L.), neem (*Azadirachta indica* A. Juss), sabadilla (*Schoenocaulon officinale* Gray), and ryania (*Ryania speciosa*) [28]. The majority of plant-derived pesticides are used to control insect pests [29,30] and also mitigate plant parasites, such as nematodes, fungi, bacteria, and viruses [31,32]. Botanical pesticides could be useful as alternative tools for integrated pest management since they have positive impacts on environmental preservation, low toxicity to mammals, and low risk of developing resistance in target pests [33–35]. Thus, this review discusses vital information regarding the status, prospects, and challenges of botanical pesticides and their possible adoption and utilization for sustainable crop management.

2. Status of Botanical Pesticides

Plants offer many bioactive compounds that are vital for the relationship that exists between plants and their environments. There are several reports on ethnobotanical plants with known pest and disease compounds, as shown in Table 1. Globally, there are about 2500 species from 235 plant families that are effective in tackling pests [30,36].

Table 1. Some botanicals, parts used, and extraction methods against targeted pests and diseases.

No.	Scientific Name	Family	Part Utilized	Extraction Method	Target Pest	Ref.
1	*Acorus calamus* L.	Acoraceae	Leaf, Rhizome, Stem	Aqueous, Ethanolic, Methanolic extraction	*Microsporum gypseum*, *Penicillium marneffei*, *Trichophyton rubrum*, *Sitophilus zeamais*	[37]
2	*Adhatoda vasica* L.	Acanthaceae	Leaf, Root, Bark, Fruit, Flower	Aqueous, Ethanolic, Methanolic extraction	*Xanthomonas oryzae*	[38]
3	*Allium cepa* L.	Alliaceae	Seed	Steam distillation	*Alternaria solani*, *Cochliobolus heterostrophus*, *Phytophthora infestans*, *Ramularia areola*	[39–41]
4	*Allium sativum* L.	Alliaceae	Bulb, Leaf	Ethanolic extraction	*Bemisia tabaci*, *Curvularia lunata*, *Fusarium guttiforme*, *Helicoverpa armigera*, *Pseudomonas syringae*	[42–45]
5	*Annona squamosa* L.	Annonaceae	Seed	Solvent extraction	*Fusarium wilt*, *Phytophthora blight*, *Rhizoctonia solani*	[46]
6	*A. indica*	Meliaceae	Leaf, Bark, Root, Seed, Fruit	Aqueous, Ethanolic, Methanolic extraction, Steam distillation	*Aphis* spp., *Aspergillus niger*, *B. tabaci*, *Colletotrichum spp*, *Echinochloa crusgalli*, *Fusarium oxysporum*, *Geotrichum candidium*, *H. armigera*, *Meloidogyne incognita*, *Meloidogyne javanica*, *Rhizopus stolonifer*, *Sitophilus zeamais*	[47–50]
7	*Camellia oleiferaAbel.*	Theaceae	Stem, Leaf	Aqueous extraction		[35]
8	*Capsicum frutescens* L.	Solanaceae	Fruit	Maceration, Soxhlet, Ethanolic extraction	*A. solani*, *Bacillus subtilis*, *Escherichia coli*, *F. oxysporum*, *Phytophthra infestans*, *Pseudomonas aerugionsa*, *Staphylococcus aureus*	[41,51,52]
9	*Chromolaena odorata* L.	Asteraceae	Leaf, Stem, Root	Aqueous, Ethanolic, Methanolic extraction	*A. niger*, *Dolichodorus* sp., *F. oxysporum*, *G. candidium*, *Helicotylenchus* sp., *M. incognita*, *R. stolonifer*	[49,53]
10	*Chrysanthemum cinerariaefolium* L.	Compositae	Flower	Ethanolic, Methanolic extraction	*Blatta orientalis*, *Isoptera* spp., *Lasius niger*, *Myrmecia gulosa*	[47]
11	*Citrus hystrix* DC.	Rutaceae	Leaf	Steam, Hydrodistillation, Solvent extraction	*Acarina* spp., *Acheta domesticus*, *Aphis* spp., *Botrytis cinerea*, *Siphonaptera* spp., *Uromyces appendiculatus*,	[44,54]
12	*Coriandrum sativum* L.	Apiaceae	Seed, Fruit	Steam, Hydrodistillation, Solvent extraction	*Alternaria alternate*, *F. oxysporum*, *Pyricularia oryzae*, *Trichoconiella padwickii*, *X. oryzae*	[55]
13	*Croton chichenensis* Lundell	Euphorbiaceae	Root	Aqueous, Ethanolic extraction	*Alternaria tagetica*, *Colletotrichum gloeosporioidese*, *F. oxysporium*, *Rhizopus* sp.	[56]

Table 1. *Cont.*

No.	Scientific Name	Family	Part Utilized	Extraction Method	Target Pest	Ref.
14	*Cymbopogon citratus* Stapf.	Gramineae	Leaf	Maceration, Hydro, Steam distillation	*A. solani*, *Alternaria brassicae*, *P. infestans*, *Pectobacterium carotovorum*	[57]
15	*Curcuma longa* L.	Zingiberaceae	Root stem	Aqueous extraction	*Spodoptera frugiperda*, *Spodoptera litura*	[58–60]
16	*Datura stramonium* L.	Solanaceae	Leaf, Fruit	Methanolic extraction, solvent extraction	*A. alternata*, *Aspergillus flavus*, *Aspergillus fumigatus*, *A. niger*	[61,62]
17	*Eucalyptus globules* Labill	Myrtaceae	Leaf, Bark	Steam, Hydro distillation, Soxhlet extraction	*A. brassicae*, *Alternaria triticina*, *A. solani*, *F. oxysporum*, *P. infestans*, *Pythium ultimum R. solani*	[63–65]
18	*Gossypium herbaceum* L.	Malvaceae	Leaf	Crude, Solvent extraction	*Rice stripe virus*, *Southern rice black-streaked dwarf virus*, *Tobacco mosaic virus*	[66]
19	*Hydnocarpus anthelminthicus* Pierre ex Lecomte	Achariaceae.	Leaf, Fruit.	Aqueous, Ethanolic extraction	*Colletotrichum falcatum*, *Colletotrichum higginsianum*, *Phytophthora palmivora*, *P. oryzae*, *R. solani*	[67,68]
20	*Lantana camara*	Verbenaceae	Leaf, Stem, Fruit	Maceration, Solvent, Aqueous, extraction, Steam distillation	*A. flavus*, *A. niger*	[69,70]
21	*Derris elliptical*	*Fabaceae*	Root	Crude extraction	*Aphis* spp., *Cerotoma trifurcata*, *Diabrotica undecimpunctata*, *Erythroneura variabilis*, *Tetranychus urticae*	[47]
22	*Mentha piperita* L.	Lamiaceae	Shoot	Steam, Hydro distillation	*A. alternata*, *B. cinerea*	[71,72]
23	*N. tabacum*	Solanaceae	Leaf	Solvent extraction	*Aphis* sp., *Acarina* sp., *Bradysia* sp., *Circulifer tenellus*, *F. oxysporum*, *Penicillium digitatum*, *Rhizopus* sp.	[47,73]
24	*Ocimum basilicum* L.	Labiatae	Leaf	Steam, Hydro distillation	*A. solani*, *Alternaria heveae*, *P. infestans*	[41,74]
25	*Ocimum sanctum* L.	Malvaceae	Leaf	Ethanolic extraction	*F. oxysporum*, *Macrophomina phaseolina*, *Sarocladium oryzae*	[75–77]
26	*Ocimum tenuiflorum* L.	Lamiaceae	Leaf	Crude extraction	*Phyllosticta zingiberi*	[78]
27	*Origanum vulgare* L.	Lamiaceae	Leaf, Flower	Aqueous, Ethanolic extraction	*Bacillus spp.*, *Serratia marcescens*	[79]
28	*Peganum harmala* L.	Zygophyllaceae	Leaf, Stem	*n*-Butanol extraction	*Bursaphelenchus xylophilus*	[80]
29	*Prosopis juliflora* (Sw) DC	Fabaceae	Leaf, Fruit	Ethanolic extraction	*A. alternata*, *A. solani*, *B. cinerea*, *B. subtilis*, *Candida albican*, *Geotrichum candidum*, *P. infestans*, *S. aureus*, *Xanthomonas campestris*	[81]
30	*Psidium guajava* L.	Myrtaceae.	Leaf	Aqueous, Ethanolic, Methanolic extraction	*Chromobacterium violaceum*, *P. carotovorum*, *Pseudomonas aeruginosa*, *S. aureus*, *S. marcescens*	[57,82]
31	*Reynoutria sachalinensis* Schmidt	Polygonaceae.	Leaf, Stem, Flower	Aqueous, Ethanolic extraction	*Leveillula taurica*	[83,84]

Table 1. *Cont.*

No.	Scientific Name	Family	Part Utilized	Extraction Method	Target Pest	Ref.
32	*Ricinus communis* L.	Euphorbiaceae	Leaf	Methanolic extraction	*R.solani*, Fusarium wilt	[46]
33	*Rhododendron molle* G.Don	Ericaceae	Flower	EtOAc extraction	*Pieris rapae*	[85]
34	*Rosmarinus officinalis* L.	Lamiaceae	Leaf, Seed	Steam, Hydro distillation	*A. flavus*, *Phytophthora capsici*, *P. megakarya*, *P. palmivora*	[86]
35	*Salvia officinalis* L.	Lamiaceae	Shoot	Soxhlet extraction, Hydrodistillation	*Penicillium aurantiogriseum*, *Verticillium dahlia*	[87]
36	*Tithonia diversifolia* (Hemsl.)	Asteraceae	Leaf	Crude, Methanolic extraction	*A. niger*, *F. oxysporum*, *G. candidium*, *R. stolonifer*	[59]
37	*T. diversifolia*	Asteraceae	Leaf	Crude, Methanolic extraction	*Cercospora arachidicola*, *Cercosporidium personatum*	[88]
38	*Tridax procumbens* L.	Asteraceae	Leaf	Crude, Methanolic, Soxhlet extraction	*C. arachidicola*, *C. personatum*	[88]
39	*Thuja orientalis* L.	Cupressaceae	Leaf	Aqueous extraction, Steam distillation	*Watermelon mosaic virus*	[89]
40	*Thymus citriodorus* L.	Lamiaceae	Leaf	Maceration, Soxhlet extraction, Steam distillation	*M.incognita*, *M.javanica*	[51]
41	*Trigonella foenumgraceum* L.	Fabaceae	Leaf, Seed	Ethanolic, Methanolic extraction	*P. capsici*	[90]
42	*Vernonia amygdalina* Del.	Asteraceae	Leaf	Maceration, Soxhlet extraction	*F. oxysporum*	[64]
43	*Withania somnifera* L.	Solanaceae	Leaf	Aqueous extraction	*Trichothecium roseum*	[91]
44	*Zingiber officinale* Roscoe.	Zingiberaceae	Rhizome	Maceration, Crude, Solvent extraction	*B.tabaci*, *Caliothrips fasciatus*, *Colletotrichum lindemuthianum*, *Fusarium lycopersici*, *F. oxysporium*, *F. solani*, *Phaeoisariopsis*, *griseola*, *P.infestans*, *P. oryzae*, *P. digitatum*	[44,92,93]

Bioactive Compounds from Botanicals

In ancient times, plant species and their secondary metabolites were exploited, especially in herbal traditional cultures [94]. Most times, plant species from different families might have related chemical structures for defense, such as isoflavonoids in the Fabaceae and sesquiterpenes in the Solanaceae [95]. Diverse studies established that botanical pesticidal constituents comprise a variety of isolated secondary metabolites that have behavioral and physiological effects (repellence, oviposition, feeding deterrence, acute toxicity, developmental disruption, and growth suppression) on agriculturally important pests and diseases [96].

Hyoscyamine, Atropine, and Scopolamine are bioactive compounds found in Datura, and they indicate repellent and oviposition deterrent activity against insect pests [97]. Calatropin and Calotoxin are bioactive ingredients present in calotropis, which manifest as antifeedant, repellent, oviposition deterrent, and insect growth regulator activities against insect pests [98,99]. Meanwhile, Vasicine, Vasicinone, and Adhatodin are bioactive ingredients available in the Adhatoda, and they exhibit repellent and insecticidal activity on insect pests [100,101]. Karanjin is the bioactive ingredient present in *P. pinnata*. It indicates antifeedant, Juvenile Hormone Analogue (JHA), and insecticidal activity against insect pests [102]. Furthermore, Azadiractin, Melantriol, Nimbinin, Nimbidin, Salanin, Nimbin, Nimbolin A, and Nimbolin B are the bioactive ingredients present in the neem leaf extract. These compounds show antifeedant, repellent, oviposition deterrent, and insect growth regulator activity against pests [25,103]. Allicin and diallyl sulfide are the bioactive ingredients present in garlic extract, which have insecticidal activity [104]. Chili extract contains Capsaicin as the active ingredient that has repellent and deterrent activity against insect pests [105]. Meanwhile, Lantanolic acid and Lantic acid are the bioactive compounds present in Lantana, which exhibit growth inhibition and repellent activity against pests [106]. Anonaine and squamocin are bioactive ingredients present in *A. squamosa*, which show feeding deterrent activity against pests [107]. However, these compounds have considerable benefits and are precursors in sustainable agriculture [108,109].

Botanical pesticidal compounds have noticeable effects against various agricultural pest species because of their varied mechanisms of action [110,111]. It has been shown that plant-based pesticides act specifically in the insect nervous system; affect γ-aminobutyric acid (GABA), gated chloride channels, and sodium channels; and competitively combine acetylcholinesterase, nicotinic acetylcholine receptors (nAChR), octopamine, and tyramine receptors [112,113]. All these possible mechanisms are shown in Tables 2 and 3.

Table 2. Some commercial botanical pesticides, bioactive compounds, and biological effects.

No.	Product	Botanical Name	Trade Name	Main Bioactive Compound(s)	Biological Effects	Ref.
1	Capsicum oleoresin	*Capsicum* spp. (*C. frutescens*)	Hot Pepper Wax Insect Repellent	Capsaicin	Repellent, Fungicide, Nematicide, Bactericide	[114,115]
2	Cinnamaldehyde	*Cassia tora* L., *Cassia obtusifolia* L.	Vertigo™, Cinnacure™,	Cinnamaldehyde	Fungicide, Insect Attractant	[114,115]
3	Cinnamon essential oil	*Cinnamomumzeylanicum*	Weed Zap™, Repellex,	Cinnamaldehyde	Insecticide, Herbicide	[96,116]
4	Clove essential oil	*Syzygium aromaticum* L. *Eugenia caryophyllus* Spreng	Matran EC, Burnout II, Biooganic Lawn	Eugenol (mixture of several predominantly terpenoid compounds)	Insecticide, Herbicide	[96,114–116]
5	Extract of giant Knotweed	*R. sachalinensis*	Milsana®, Regalia™	Physcion, Emodin	Fungicide, Bactericide	[112,115]
6	Jojoba essential oil	*Simmondsia californica* Nutt., *S. chinensis*	Detur, E-Rasem, Eco E-Rase, Permatrol, ERase™	Straight-chain wax esters	Fungicide, Insecticide	[114,115]
7	Karanjin	*Derris indica* (Lam.) Bennet	Derisom	Karanjin	Insecticide, Acaricide	[114]
8	Lemongrass essential oil	*Cymbopogon nardus*, *C.citratus*, *Cymbopogon flexuosus* D.C	GreenMatch EX™	Citronellal, Citral	Insecticide, Herbicide	[96,115]
9.	Neem (neem oil, medium polarity extracts)	*A. indica*	Ecozin, Azatrol EC, Agroneem, Trilogy™	Azadirachtin, Dihydroazadirachtin, Triterpenoids (Nimbin, Salannin	Insecticide, Acaricide, Fungicide	[114,117]
10	Nicotine	*Nicotiana* spp.	Stalwart, No-Fid, XL-All Nicotine, Tobacco Dust	(S)-isomer, (RS)-isomers, and (S)-isomer of nicotine sulfate.	Insecticide	[114,117]
11	Phenethyl propionate	Component of peppermint oil (*M. piperita*) and peanut oil	EcoSmart HC, EcoExempt HC, Ecopco Acu	Phenethyl propionate	Insecticide, Insect Repellent, Herbicide	[114,115]
12	Pink plume poppy extract	Macleaya cordata R. Br.	Qwel®	Alkaloids, Anguinarine Chloride, Chelerythrine Chloride	Fungicide	[112,115]

Table 2. *Cont.*

No.	Product	Botanical Name	Trade Name	Main Bioactive Compound(s)	Biological Effects	Ref.
13	Pyrethrum	*Tanacetum cinerariaefolium* (Trevisan) Schultz-Bip.	Pyganic, Diatect	Esters of chrysanthemic acid and pyrethric acid (pyrethrins I and II, cinerins I and II, jasmolins I and II)	Insecticide, Acaricide	[115,117]
14	Rosemary essential oil	*R. officinalis*	Ecotrol™, Sporan™	1,8-cineole (borneol, camphor, monoterpenoids)	Insecticide, Acaricide, Fungicide	[96,115]
15	Rotenone	*Derris* spp., *Lonchocarpus* spp., and *Tephrosia* spp.	Bonide, Rotenone	Rotenone, Deguelin, (isoflavonoids)	Insecticide, Acaricide	[114,117]
16	Ryania	*Ryania* spp. (*Ryania speciose* Vahl)	Natur-Gro R-50, Natur-Gro Triple Plus, Ryan 50	Ryanodine, Ryania, 9,21-didehydroryanodine (alkaloids)	Insecticide	[114,117]
17	Sabadilla	*Schoenocaulon* spp. (*S. officinale*)	Veratran, Red Devil, Natural Guard	Mixture of alkaloids (cevadine, veratridine)	Insecticide	[115,117]
18	Thyme essential oil	*Thymus vulgaris* L. *Thymus* spp.	Proud 3, Organic Yard Insect Killer, Promax™	Thymol, Carvacrol	Insecticide, Fungicide, Herbicide	[96,115]

Table 3. Mechanism of action of some botanicals.

No.	Plant Source	Active Compounds	Target Site	Mechanism of Action	Ref.
1	*Haloxylon salicornicum*, *N. tabacum*, *Stemona japonicum*	Nicotine	Nervous system	It competes with the neurotransmitter by attaching to acetylcholine receptors (nAChRs) at neuron synapses, producing unregulated nerve firing. The disturbance of normal nerve impulse performance caused physiological system malfunctions of the neurons.	[118–120]
2	*Crysanthemum cinerariaefolium*	Pyrethrin I & II, Cinerin I & II, Jasmolin I & II	Nerve (Axon)	Interfering with Na and K ion conversion inhibited normal transmittal of nerve impulses, triggering paralysis in insects.	[17,121,122]
3	*Lonchocarpus* spp., *Derris* spp.	Rotenone	Mitochondria	Cell respiratory enzyme inhibitor disrupts cellular metabolism, reduces ATP output. Nerve and muscle cell malfunctions lead to low feeding rates.	[123–125]
4	*Ryania* spp.	Byanodine	Muscles	Activation of sarcoplasmic reticulum. Affect calcium development and causes improper function of muscles.	[126]
5	*S. officinale*	Sabadilla	Nerve (Axon)	Obstruct the movement of neurons and potassium ion in nerve axons.	[122,127]
6	*Cedrus* spp., *Citronella* spp., *Eucalyptus* spp., *Pinus* spp.	Essential oils	Octopaminergic system	Increase the level of intracellular messenger and effectively inhibit cyclic AMP of abdominal epidermal tissue.	[122,128]

Table 3. *Cont.*

No.	Plant Source	Active Compounds	Target Site	Mechanism of Action	Ref.
7	*Monarda* spp., *O. vulgare*, *T. vulgaris*	Thymol	Octopaminergic system	Prevent octopamine receptors via tyramine receptors cascade.	[122,129]
8	*A. indica*	Azadirachtin, Nimbin, Salannin, Melandriol	Endocrine System	Inhibit Prothoracicotropic hormone (PTTH); distort phagostimulant disruptor by cholinergic transmission	[122,130,131]
9	*A.squamosa*	Squamocin (annonin), Debitterized annona oil	Mitochondria	Dunnione acts as insecticide and fungicide, disrupting mitochondrial complex III.	[122,132]
10	*Capsicum annum*	Protoalkaloids Capsaicin	Nerve	Induced metabolism, impaired cell membrane, and nervous system. Acts as a physical repellent.	[132]
11	*Citrus sinensis*	Limonene, Linalool		Hyperactivity, hyperexcitation leading to rapid knockdown and immobilization. Inhibitory effects on acetylcholinesterase.	[133]
12	*Pongamia pinnata*	Karanjin, Debitterised karanjin oil		Serves as feeding restraint, repellant, reduced growth, oviposition suppressor, and low or no fertilization.	[122,132]
13	*S. officinale*	Cevadine, Veratridine	Mitochondria	Interrupt nerve cell membrane process, induced nerve cell membrane, paralysis, and mortality.	[122,132]

3. Application of Botanical Pesticides

Many plant-based pesticides have been discovered, but significant amounts have yet to be isolated and analyzed to identify their bioactive ingredients. These sizeable sources of botanicals have been underutilized and neglected as pesticidal agents to manage a plethora of destructive pests and diseases. Thus, the application of botanicals as pesticidal agents and their effectiveness as alternative pest management in sustainable agricultural and in related fields have been researched. The products are utilized as insect repellents, antifeedants, insecticides, and insect growth inhibitors. Moreover, these botanical bioactive ingredients are applied as nematicides, fungicides, bactericides, and virucides, as shown in Figure 1. Apparently, several plants have pesticidal potential, vast research has been carried out, and several kinds of efficacies have been confirmed.

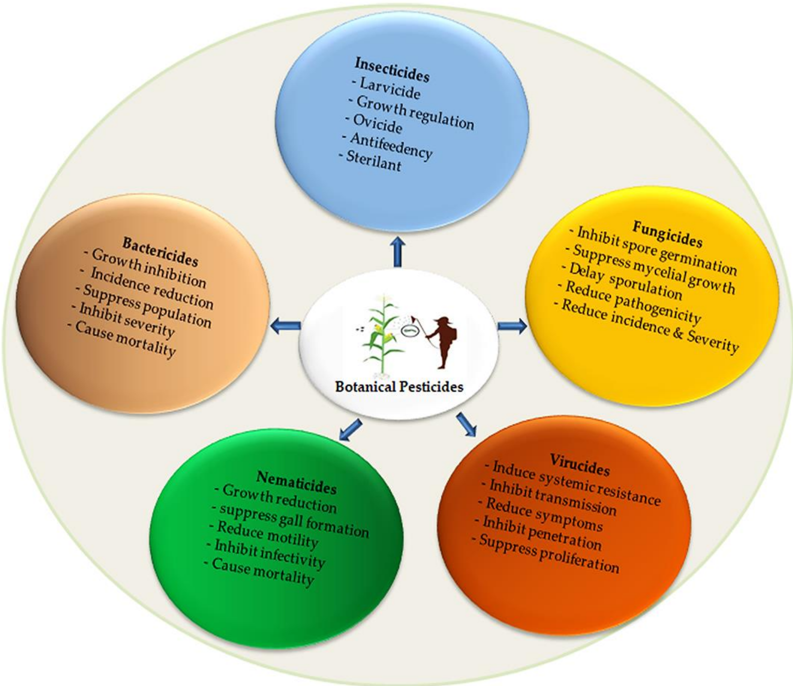

Figure 1. Illustration of botanical pesticides application in agriculture.

3.1. Insecticidal Activities

Botanical pesticides, such as *A. indica*, *A. sativum*, *C. cinerariaefolium*, *Datura metel*, *Hyptis suaveolens*, L. *camara*, *Mirabilis jalapa*, *R. speciose*, and *Tagetes minuta* have been utilized to manage common bean (*Phaseolus vulgaris* L.) pests, including aphids, armyworms, bean leaf spot, bollworm, cabbage loopers, caterpillars, common grasshoppers, bruchid beetle, pink stalk borer, and thrips [134]. *Carica papaya* L. and *T. minuta* extracts were the most potent in suppressing the abundance of aphids and damages caused to the leaves. This might be because of the different insecticidal constituents contained in these plant materials [135]. The *C. papaya* leaf extract contains groups of cysteine protease enzymes such as papain, alkaloids, terpenoids, flavonoids, and non-protein amino acids that are deleterious to plant-sucking insect pests, including aphids, spotted bollworms, and whiteflies [136,137]. *T. minuta* leaf extracts possess different insecticidal compounds, such as phenylpropanoids, carotenoids, flavonoids, phototoxin alphaterthieenyl, and thiophenes, which are effective in controlling insect pests [138].

Azadirachtin exhibits multiple modes of action, which include antifeedancy, detrimental effects on morphology, alteration in biological fitness, fecundity suppression, decreased growth, oviposition repulsive, and even sterilization [139,140]. Azadirachtin induced harmful metamorphic effects, such as a slow rate of pupation time as well as reduced growth from larva-to-pupa, in *D. melanogaster*, *S. frugiperda*, and *Callosobruchus maculatus* [141,142]. Moreover, extract from neem bark exhibited anti-lepidopteran potency that was highly significant relative to neem leaf extracts because of its higher azadirachtin and nimbin contents [143]. Interestingly, there was an increase in the level of mortality and morphological impairments of the wings, legs, and scutellum based on the increase in the concentration of neem oil [144]. Leaf extracts from *A. indica*, *O. sanctum*, and *Eucalyptus globulus* had significant insecticidal activity against *Aphis gossypi* and *Phenacoccus solenopsis* in vitro [145]. Furthermore, neem leaf extract resulted in a significant decrease in the number of eggs laid and survival rates of adults of grains/seeds storage pests at a concentration of 1.5 mg/100 g [143]. An enrichment of organic fertilizers with neem leaf powder and boiler ash was observed to significantly improve the resistance of plants against aphids [146]. Azadirachtin induced lethal toxicity during the pupal phase, causing significant morphological impairments and prolonging the adult formation in *D. melanogaster* [140]. In a previous study, it was confirmed that 20 uM azadirachtin induced robust developmental caused a delay in the larva-to-pupae phase and resulted in molting defect [147]. Furthermore, higher concentrations of azadirachtin (0.1 and 1.0 µg) hindered growth in the third instar of *Lutzomyia longipalpis* (Diptera) [148]. In addition, azadirachtin caused deformity of larvae, pupae, and adult, reduction in protein synthesis of pupae, low hemolymph volume during last instar larvae, inhibit enzyme activities of larvae gut, and lower cuticular protein level changes of larvae of *S. litura* [149,150]. Furthermore, azadirachtin had strong antifeedant impacts on *D. melanogaster*, *Plutella xylostella*, and *Galleria mellonella* [151,152]. Sublethal effects of azadirachtin, i.e., alteration in mating and post-mating behavior [153] and low rate of fecundity in *D. melanogaster* [154], were also reported. Several findings revealed that azadirachtin disrupted juvenile hormone and 20-hydroxyecdysone pathways, which resulted in partial larval development, sterile eggs, and decreased fecundity [155,156]. Azadirachtin led to 100% mortality after treating tobacco whitefly *B. tabaci* for 72 h through oral ingestion [142]. The mortality of the pollinator *Bombus terrestris* (Hymenoptera) ranged from 32 to 100% once exposed to azadirachtin at concentrations between 3.2 and 320 mg/L after 11 weeks [157].

Under laboratory conditions, 10% turmeric dust induced 80% mortality in rice pests (*Cnaphalocrosis medinalis*, *Oxya nitidula*), eggplant pests (*Aphis gossypii*, *Coccidohystrix insolitus*, *Epilachna vigintioctopunctata*, and *Urentius hystricellus*), okra pests (*Amrasca devastans*, *Anomis flava*, *Dysdercus cingulatus*, *Earias vittella*, *Oxycarenus hyalinipennis*, *S. litura*, and *Tetranychus neocaledonicus*), respectively [158]. Moreover, there was an inhibitory effect on the feeding activity at the first and second instar of *S. frugiperda* caterpillars when exposed to the turmeric, clove, and palmarosa plant oils [159].

Furthermore, essential oils could act as antifeedants, repellants, and oviposition deterrents which serve as larvicide, ovicide, and insecticide, thereby exhibiting compounds that interfere in all phases of insect metamorphosis [160]. The essential oil extracted from turmeric leaves and applied as contact or fumigant is efficacious against three main stored-product beetles, *R. dominica*, *Sitophilus oryzae*, and *Tribolium castaneum* [161]. Again, some essential oils, such as eucalyptus and rosemary, exhibit repellent effects against several insect species, including vectors [162]. The toxicity of eucalyptus and rosemary essential oils caused a neurotoxic mode of action in some insects, which caused hyperactivity and was followed by hyperexcitation, leading to a rapid knockdown and immobilization [163]. Allicin extracted from garlic bulbs (*A. sativum*) resulted in the suffocation of insect pests due to its negative effects on neurotransmitter receptors [164]. Ethanolic extracts of 2.08% to 5.80% (*w/w*) from *Tagetes* spp. inhibited growth and development of *S. frugiperda* [165]. Leaf powder of *E. globulus* showed insecticidal activity against *Prostephanus trunatus* [166]. The leaves powdered from *Dalbergia saxatilis* possessed protectant properties against cowpea bruchid, *C. maculatus*, which served as a respiratory poison [167]. For *Piper guineense*, *P. longum*, and *P. retrofractum* extracts caused 96–100% mortality rate in 48 hours of the management of *C. maculatus*, *Zonocerus variegatus*, and mosquito larvae [168]. *O. sanctum* oil (1000 ppm) caused 13.33% larval mortality in fourth instar larvae of *S. litura* [169,170].

In addition, saunf and khas oil led to the highest mortality (100%) and followed by clove oil (93.33%). The lowest larvae weight was seen in clove oil (−0.025 g and −0.06 g) at 1 and 2%, respectively [171]. Findings revealed that rhizome and its aerial part extract offered dose mortality activity towards *T. castaneum* adults [172]. *Isodon rugosus* and *Daphne mucronata* plant extracts act as possible pesticides against pea aphid, *Acyrthosiphon pisum* [173]. Onion (*A. cepa*) and ginger (*Z. officinale*) were assessed for effectiveness on tomato fruit worm (*Helicoverpa zea)*, which resulted in a 70–80% decrease compared to control [42]. Over 50% rape aphids (*Brevicoryne brassicae*) and tomato red spider mites (*Tetranychus evansi*) were decreased by powder extracts from *Lippia javanica* and *Solanum delaguense* [174]. Extracts from *Curcuma longa*, *A. sativum*, and *Ferula assafoetida* significantly decreased both larvae and pupa of *H. armigera* [175]. *Artemisia herbaalba*, *Eucalyptus camaldulensis*, and *R. officinalis* extracts were applied on broad bean leaves, which led to 60–100% mortality of *Myzus persicae* after 24 hours of exposure in dose-dependent in vitro experiments [176]. An increase in concentrations of extracts from *C. longa* and *A. sativum* resulted in high mortality rates, reduced weight, and serve as anti-molting properties on larvae, pupa, and adults of *T. castaneum* [177]. Similarly, *Eucalyptus terreticonis*, *Tagetes minuta*, and L. *camara* extracts induced mortality of *S. zeamais* adults [178].

3.2. Fungi Management

Extracts from many plant species are discovered to be efficacious against several plant pathogenic microorganisms without imposing ill side effects. In addition to inhibiting germ tube elongation and mycelial development, plant-based bioactive compounds, including alcohols, alkaloids, phenols, tannins, and terpenes delay sporulation, DNA, and protein synthesis [179,180]. Moreover, they altered the structure of hypha and mycelia, inhibiting the production of toxic substances from mycotoxin-producing fungal such as *Aspergillus* spp. and *Fusarium* spp.; thus, reducing their pathogenicity [181]. Furthermore, curcumin had fungicidal activity against *P. infestans*, *P. recondita*, and *R. solani* with 100 and 63% at 500 mg/L, and 85%, 76%, and 45% at 250 mg/L, respectively [182]. Extracts of pawpaw leaves at concentrations of 20%, 40%, 60%, and 80% were more potent against *A. solani* [183]. Extracts from *Ocimum gratissimum* and *E. globules* inhibit wilting in cowpea seedlings induced by *Sclerotium rolfsil* from 39.6% for untreated to 4–12% for treated plants [64]. Methanol extract of turmeric rhizomes controlled the growth of anthracnose on red pepper caused by *Colletotrichum coccodes* [184]. The curcuminoids effectively inhibited the mycelial growth of three red pepper anthracnose pathogens, *C. coccodes*, *C. gloeosporioides*, and *C. acutatum*, in a range of 0.4–100 µg/mL [183]. Reports revealed turmeric essential oil and curcumin against plant pathogenic bacteria and fungus effectively [185,186]. Extracts from *Ricinus communis* effectively inhibited the growth of post-harvest pathogens *Penicillium oxalicum* and *A. niger* of yams [187].

Additionally, the prevalence of tomato fruit rot in many parts of Africa could be curtailed significantly with extracts from *Cassia alata*, *Alchornea cordifolia*, and *Moringa oleifera* as postharvest agents [188]. Post-harvest fungi, including *F. solani*, *Rhizopus arrhizus*, and *Sclerotium rolfsii*, were controlled after using extracts from *Duranta erecta* and *Lasonia ineruis* [189]. *Fusarium verticillioides* was treated with different plant extracts, causing cell wall disruption, loss of cellular components, and suppressed fumonisin and ergosterol production [190]. Whereas alcoholic extracts from suicide tree (*Cerbera odollam*), clove (*S. aromaticum*), and mahogany (*Swietenia macrophyllai*) at 3000 ppm repressed the growth of *A. niger*, *Penicillium digitatum*, and *Fusarium* sp. by 40–90% in citrus [145]. Botanical extracts have been shown to successfully mitigate late blight of potato (*Phytophthora infestans*) and *Fusarium wilt* of legumes [191,192]. Again, ginger extracts reduced the cytoplasm and changed the microconidia morphology of *Fusarium* sp. [193]. Extracts from *Piper nigrum*, *Cinnamomum zeylanium*, and *C. cassia* were reported as strong repellents to reduce the population of *Megalurothrips sjostedti* [194]. *F. oxysporum* f. sp. ciceris, a pathogen causing wilt of chickpea (*Cicer arietinum*) by up to 50%, could be controlled with methanolic extracts of *Chenopodium ambrosioides* [195].

A study found that neem (*A. indica*) and Mexican sunflower (*T. diversifolia*) extracts declined the growth of tomato rot disease, *A. niger*, *F. oxysporum*, and *G. candidium* up to 100% [49]. Allicin was reported to cause morphological abnormalities, including collapsing, thinning, and damaging of hyphal strands, thus, inhibiting germination of spores and hyphal growth [196]. *A. sativum*, *Copaifera langsdorfii*, *C. zeylanicum*, and *Eugenia caryophyllata* essential oils significantly reduced anthracnose of banana via immersion [197].

3.3. Bacteria Management

The botanical compositions also have multiple antibacterial properties. A study showed that acetone extracts of *Aloe vera* influenced growth of *P. aeruginosa*, while its methanolic extracts inhibited *E. coli* and *B. subtilis*. The phytochemicals that denature microbe proteins and disrupt their functionality were supposed to result in the antimicrobial activity of *A. vera*. For instance, cinnamic acid inhibits glucose uptake and ATP production [198]. Some botanical pesticides inhibited cellular processes against bacteria, and increased permeability of plasma membrane could lead to leakage of cell contents and cell death [199]. As for the essential oils of *T. vulgaris*, the presence of thymol causes membrane permeability and depolarization, resulting in the interference of cell mechanisms of *Bacillus cereus*, *Klebsiella pneumonia*, *S. aureus*, *Salmonella typhimurim*, and *Escherichia coli* [79,200].

D. metel substantially reduced the growth of *X. oryzae* pv. oryzae in vitro, and decreased bacterial leaf blight of rice in greenhouse, which mainly resulted from daturilin presence [201]. Utilization of *D. metel* as a seed treatment, root dip at transplanting time, and foliar spray influenced superior effectiveness against *X. oryzae* pv. oryzae in rice intensity by 59.17% in greenhouse and 46.02% in microplots as compared to control [202]. Cold and hot water extracts of leaves from *Datura*, *Garlic*, and *Nerium* applied two days pre-inoculation and two days post-inoculation on Super Marmande tomato cultivars considerably lowered the disease index of *R. solanacearum* wilt in greenhouse experiments [203]. Furthermore, [201] discovered that several plant extracts, including *D. metel*, *A. indica*, *Ipoma cornea*, *Vitex negunda*, and *Zizyphus jujuba*, had antibacterial properties against *Xanthomona campestris* pv. oryzae.

Under greenhouse and field trials, aqueous extracts of *Hibiscus sabdariffa*, *Punica granatum*, and *E. globulus* were found to effectively protect potato plants against bacterial wilt (*R. solanacearum)* [204]. *A. sativum* extract was extremely effective in safeguarding tomato plants against *P. syringae* pv., *Xanthomonas vesicatoria*, and *Clavibacter michiganensis* subsp., respectively [205]. *A. sativum* extract reduced the incidence of tomato bacterial wilt *R. solanacearum* population when applied to soil in vitro experiments [203]. Similarly, when compared to the leaf extract from *L. camera* and the bulb extract from *A. sativum*, the aqueous leaf extract from *A. vasica* was found to be extremely effective in preventing the growth of *X. oryzae* pv. oryzae [206].

Thymol and palmarosa oil were utilized for preplant soil fumigation and successfully reduced the incidence of tomato bacterial wilt (*R. solanacearum*) [207]. Oils of palmarosa and lemongrass were found to inhibit the growth of *R. solanacearum* race 4 (phylotype I) in potting media, as well as the occurrence of bacterial wilt in edible ginger [208]. In both greenhouse and field, soil biofumigation using *palmarosa* essential oil inhibited the severity of bacterial wilt of sweet peppers [209]. In vitro conditions, extract from *A. fistulosum* of 50 and 100% decreased growth of *R. solanacearum*, and preplant treatment of the soil with *A. fistulosum* considerably declined the *R. solanacearum* population compared to control [210]. *C. longa* decoctions were the most effective in controlling bacteria leaf blight (BLB) in rice plants, both in the lab and field [211]. Again, [212] ascertained that using neem gold (20 mL/L) decreased bacterial blight severity and increased rice yield.

3.4. Nematodes Management

Death in second-stage juveniles of root-knot nematode (*Heterodera cajani)* was influenced by essential oils derived from pesticidal plants [213]. Again, lipophilic phytochemicals could easily disintegrate the cytoplasmatic membrane of nematodes by hindering protein structures that serve to enhance growth, development, and survival [214]. The crushed leaves of African 17 marigolds have been utilized by some farmers to manage nematodes [215]. Some plant constituents have affected the soil microbes population, which led to a reduction in eggs and survivability of the larvae of nematodes [216]. Whereas some compounds caused second-stage larvae mortality and toxicity, reduced egg mass and galling, which suppressed nematode accumulation level [217]. Under controlled conditions, the use of L. *camara* and *Trichoderma harzianum* inhibited reproduction rate, egg masses, and gall formation in root-knot nematodes in tomato crops [31]. Meanwhile, a decrease in the number of eggs hatched, mobility, and death of juveniles of root-knot nematode at the second stage was ascribed to bioactive compounds, including alkaloids, tannins, and glycosides presence [218,219]. It has been discovered that active compounds extracted from pesticidal plants could cause paralysis and limit infectivity potential of juvenile root-knot nematodes [220].

Under laboratory study, aqueous extracts from *C. grandis*, *C. benghalensis*, *L. cephalotes*, *P. amarus*, and *T. portulacastrum* recorded high nematicidal efficacy on egg hatchability and juvenile mortality of *M. incognita* [221]. The aqueous extracts from bark, leaf, and seed of *Cassia siamea*, *Cassia sieberiana*, *Dolnix regia*, *Isoberlinia doka*, *Tamarindus indica*, *Ocimum gratisimmum*, *and H. suaveolens*, drastically reduced egg hatching of *M. incognita* [222,223]. According to [224], their result showed that 24 h exposure of extract from dry leaves from neem influenced juvenile mortality (100%) compared to untreated. More so, freshly chopped leaves from *P. amarus* at a rate of 100 g/pot induced a high root gall index and affected the population of egg masses and *M. incognita* in the soil [221].

3.5. Viruses Management

Some plant compounds are found to induce systemic resistance of the host plants with antiviral properties by inhibiting the transmission of viruses and killing insect vectors [32]. Moreover, studies have reported that these plant compounds inhibit virus penetration and replication, hemagglutination, and enzymatic activity [225,226]. Under laboratory conditions, Tobacco Mosaic Virus (TMV) was highly affected by acetone extracts from cottonseed oil. Additionally, under field conditions, Rice Stripe Virus (RSV) and Southern Rice Black Streaked Dwarf Virus (SRBSDV) diseases were reduced. Gossypol and sitosterol compounds were identified antivirals in sludge from cottonseed oil because the derivatives from gossypol and sitosterol inhibited the formation of cell fusion-activated cores and apoptosis, respectively [68]. Furthermore, extract from *T. orientalis* suppressed the proliferation of Mosaic Virus of Watermelon through a reduction in virus infection on the hypocotyls as a result of the obstruction of the release of nucleic acids [89].

At 6 g/L, extracts from *T. orientalis* and *Artemisia campestris* inhibited potato leafroll virus proliferation by 81.72 and 63.6%, respectively [227]. The study disclosed extracts from *Paronychia argentea* extraction (10 g/mL) via foliar spray within 24 hours prior to viral inoculation decreased disease symptoms, improved plant growth, and lowered Tobacco Mosiac Virus accumulation levels in treated tomato plants under greenhouse conditions [228]. Plant extracts from *Eucaluptus camaldulensis*, *Clerodendrum aculeatum*, *Haplophyllum tuberculatum*, *M. jalapa*, *Potentilla arguta*, *Boerhaavia diffusa*, *Sambucus racemose*, and *T. orientalis* inhibited plant virus infection [229,230].

Under field conditions, resistance was induced against Bean Common Mosaic Virus (BCMV) by extracts from *A. indica*, *Plectranthus tenuiflorus*, *Schinus terebinthifolius*, and *Clerodendrum inerme* [231]. *Thuja*, *Tamarix*, and *Henna* extracts inhibited Tomato Yellow Leaf Curl Virus proliferation within the 10–12 day protection period in tomato plants [232].

4. Challenges of Botanical Pesticides

Despite the stiff competition between plant-based and synthetic pesticides, the former is not common in the market [233]. Moreover, plant-based pesticide effectiveness in the field is extremely contingent on prevailing environmental and weather conditions as they are easily degradable [43]. Several problems related to contamination, preparation potency, attenuation of pesticide activity, and shelf life are evident. It is often challenging to standardize botanical pesticide dosages due to variance growth habitations, varietal differences, harvest duration, extraction methods, and storage conditions [115]. The appropriate formulation is gravely challenging because multiple bioactive constituents are evident in one plant species that differ in chemical properties [234].

There are major obstacles faced with the commercialization of plant-based pesticides viz: (a) limited supply of botanical raw materials; (b) poor standardization and quality control of the required active ingredients; (c) issues with regulatory approval, i.e., costly toxicological evaluation of the botanical pesticide [96,117]. Regardless of the minimal toxicity displayed by botanical pesticides, their regulatory implementations in agricultural production are not different from synthetic products, particularly in low-income nations [235]. Considering bottlenecks, these products need to pass through rigorous registration, environmental, and toxicological assessments processes [113,236].

5. Conclusions and Recommendations

The effectiveness of botanical pesticides to manage agriculturally economic pests is vital due to their renewable tendency, significant environmental safety, and human welfare. Plant-based pesticides are predominantly used in low-income and emerging nations to control pests because of their cost-effectiveness, availability, accessibility, and easy-to-use. Nevertheless, the discovery of the active ingredients from pesticidal plants is still at a rudimentary level. Current strives in enhancing the characterization of efficient phytochemicals and their concentrations in final products are challenging as precision and standardization are still bottlenecks. Thus, in order to enhance and promote the full utilization and adoption of botanical pesticides as safer and sustainable pest management options in integrated pest management systems, this review proposes recommendations as follows.

1. Considering the huge quantum of raw materials required to produce plant-based pesticides, intensive cultivation of plant sources should be done to ensure the availability of raw materials for industrial uses.
2. Further studies to address the limitations confronted with botanical pesticides bordering on formulations, active ingredients, application rates, storage stability, and volatility under ultraviolet light may enhance the significant commercialization of botanical pesticides.
3. In a bid to facilitate market penetration of botanical pesticides, there is a need for collaboration among researchers, investors, manufacturers, marketers, and farmers with the sole aim of sustainable benefits that must be established.
4. Addressing the huge constraints of regulatory procedures might promote feasibility and affordability of businesses that would encourage entrepreneurs, public funding of agro-programs, investors, and large pesticide companies to enhance the enterprising of botanical pesticides.
5. Regular training on easy production and application techniques by low-income farmers and extension workers to disseminate botanical pesticide usage is essential for better adoption.
6. Considering the concerns for environmental safety across the globe, there is a need to promote intensive awareness by government agencies among farmers and manufacturers by sensitizing them to the importance of switching over to botanical pesticides for a sustainable pest management approach.
7. Thus, various aspects bordering on constraints, prospects, and regulatory networks towards effective utilization, research, and development of botanical pesticides in sustainable agricultural production should be reviewed often.

The summary of the recommendations is illustrated in Figure 2 below.

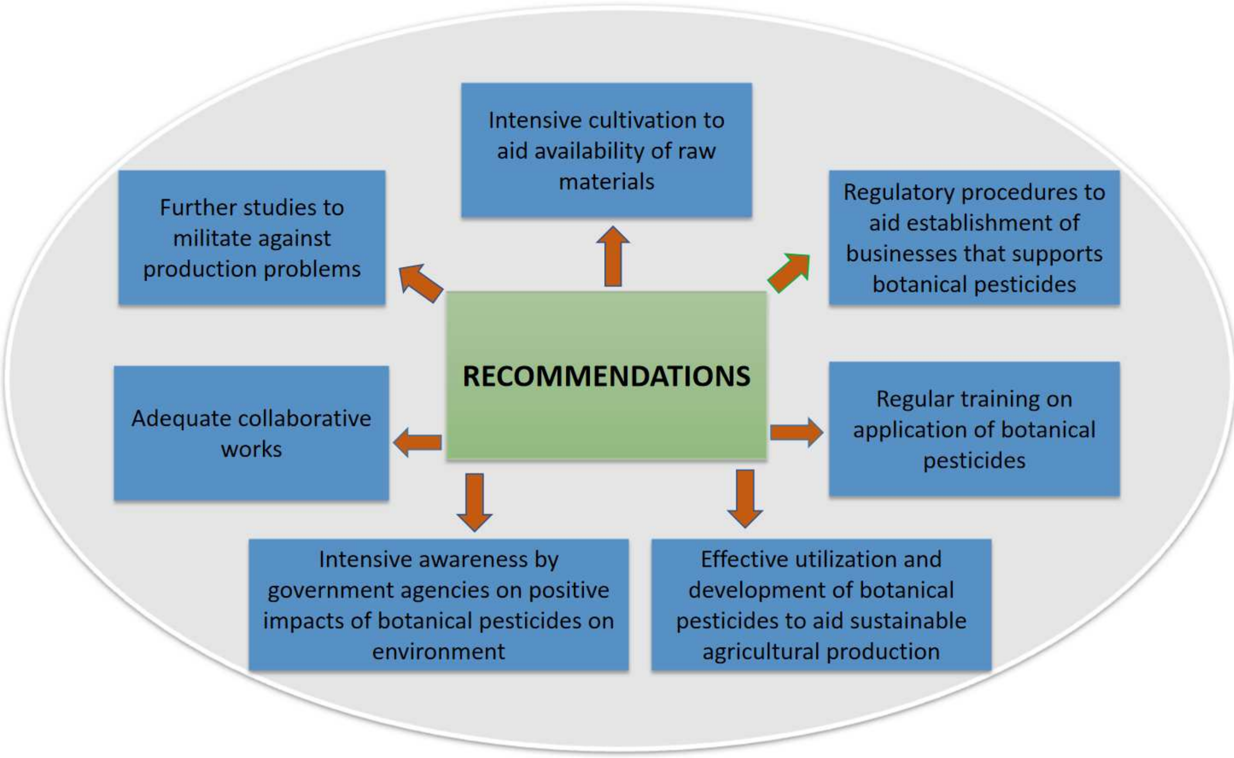

Figure 2. Recommendations to improve the use of botanical pesticides.

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