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Review Article

Reducing Postharvest Loss of Stored Grains Using Plant-Based Biopesticides: A Review of Past Research Efforts

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The world population is projected to be 9.1 billion by the year 2050, and about 70% extra food will be required. One of the main challenges regarding food security is postharvest loss due to insect pests. The overall postharvest grain losses for sub-Saharan Africa could be as high as US$4 billion/year. This is around 15% of the total production of cereal crops. The use of chemical pesticides to reduce grain damage by insects over the past five decades has led to a range of environmental and human health problems. These problems forced researchers to develop alternative methods that have lower adverse effects. Alternative strategies focus on new forms of pesticides that are effective against a specific target species, have fewer residues in food, are unlikely to contaminate the environment, and have lower potential to produce resistance, are biodegradable, and are suitable for use in integrated pest management programs. Some natural plant products effectively meet these criteria and have the potential to manage insect pests of stored grains. However, the understanding of the use of botanical pesticides in storage pest management systems is limited in most parts of sub-Saharan African countries. Effective plant products are not formulated and used widely. To fill the gaps the first step is to synthesize the available information and disseminate it. This review is, therefore, a summary of the current developments and improvements of botanical pesticides in the management of stored grain pests including challenges and future issues in insect pest management.

1. Introduction

Recently, food insecurity has become a serious issue in sub-Saharan African countries, which is reminiscent of the same issue in Asia many years earlier. The latest information showed that over the next 10 years, the world's population is predicted to increase by more than one billion people reaching 8.6 billion in 2030 and rise up to 9.8 billion in 2050 and 11.2 billion by 2100 [1]. Most of this population rise is expected in developing countries that are already facing hunger and food insecurity. Reducing agricultural yield losses could significantly contribute to satisfying the anticipated higher global food demand and improving food security [2]. Postharvest loss by insects is one of the main challenges in improving the quality of food and the achievement of food security [3]. Insect pests are the most important biotic factors, which cause huge postharvest losses in grains that range from 30 to 40% [4, 5]. According to Abass et al. [4], after six months of maize storage, the larger grain borer, *Prostephanus truncatus* (Horn), caused 57% of the storage losses, followed by the grain weevil, *Sitophilus granarius* (Linnaeus), and lesser grain borer, *Rhyzopertha dominica* (Fabricius).

Despite previous efforts [6], insect-related postharvest losses continue to be a major problem [7, 8]. The maize weevil, *Sitophilus zeamais* Motschulsky, causes severe weight and quality losses in maize grain in Africa [9]. In developing countries, storage insect pests cause 20–30% loss of maize grain during a given storage period [5, 10]. The magnitude of losses varies from country to country and from region to region [11]. For instance, in Ghana, losses were as high as 50% [12], in Cameroon's western highlands 12–44% [13], and in Benin 23% [14, 15]. In a study on postharvest losses in sub-Saharan African countries, cereals (maize and rice) incur losses of 25.6 to 27.4%, without interventions in a storage season and can be reduced when various types of loss prevention methods are applied [16]. In Ethiopia, 80% of all grain produced is stored at the farm or village level [17], which is vulnerable to insect pest attack. Tadesse and Basedow [18] reported that the proportion of damaged grains due to insect pests in Ethiopia reached up to 29.3% at farmers' storages. Tadesse et al. [19] reviewed insect pests and molds associated with stored grains in Ethiopia.

The use of conventional pesticides for many years has led to problems in agriculture, the environment, and human health [20]. It caused genetic resistance and pest resurgence of insect species, left toxic residues in the treated products, caused handling hazards and health hazards to operators [21]. Insecticides cause direct toxicity to nontarget organisms such as beneficial parasitoids and predators. They reduce several terrestrial and aquatic animal and plant species, contaminate soils, drinking water, and food, and poison pesticide users and farmworkers, and affect nontarget organisms such as bees, other beneficial insects, fish, and birds [20]. Certain chemicals get concentrated in the food chain and cause lethal effects on food consumers [22, 23]. One of the ways to minimize these problems is using biodegradable pesticides that have greater selectivity and less persistence [24]. Products of plant origin are good biodegradable agents [25], which are a rich source of bioactive molecules [26]. They are effective and more biodegradable, cause less contamination to the environment, have less potential to produce resistance, and leave fewer residues in food [27–29]. Besides, they are more economical and environmentally friendly [30]. However, plant-derived pesticides are less understood in sub-Saharan countries [31]. Therefore, this review article was an effort to summarize the current knowledge and progress related to botanical pesticides.

2. Historical Background of Botanical Pesticides

For many centuries, botanicals were used before other kinds of pesticides. They were used intensively by countries like Egypt, China, Greece, Italy, and India, where the use of the neem tree (*Azadirachta indica* Juss.; Meliaceae) was reported in the Veda, a large body of religious manuscripts written in archaic Sanskrit dated at least 4,000 years ago [32, 33]. The repellency effect of plant material has been exploited for thousands of years by human beings by placing bruised plants over the roof of the houses, a practice that is still widely used throughout developing countries. The use of plant extracts and plant parts in the form of powder as insecticides dates back at least as far as the Roman Empire [34]. During the reign of the Persian king Xerxes (400 BC), children were treated with dry flowers powders known as pyrethrum, *Tanacetum cinerariaefolium* Linnaeus (family, Compositae). Botanical insecticides were also considered an important product for pest management in Ancient China [35], Egypt, Greece, and India [36]. Historically, the use of finely ground chrysanthemum, *Chrysanthemum cinerariaefolium* (Trev) Bocc., flowers can be mentioned as the best-known example. According to preserved written documents, this plant played a very important role in fighting against obligatory ectoparasites such as lice and fleas [37].

In ancient Rome, granaries were often fumigated with various aromatic plants (Rosemary, Myrrh, and Juniper). Aromatic plants were also hung near the entry openings of the granaries. As a result, people revealed the repellent effects of aromatic plant substances [38]. From ancient times, the use of poisoned baits prepared as decoctions of *Helleborus niger* L. roots against rodents was common. In Persia, various plant oils were used to treat scabies caused by some mites, such as *Sarcoptes scabiei* L., in 1758 [39]. Later, some plants are also used for protection against phytophagous pests, with the development of intensive agricultural production. The first commercial botanical insecticide product used dated back to the 17th century is nicotine obtained from tobacco leaves showed action against plum beetles [40]. Around the mid-eighteenth century, a new plant with insecticidal property known as rotenone was introduced. It was obtained from the roots of the plant, called Timbó–*Derris* spp. [37].

3. Major Stored Grain Insect Pests

Storage insect pests reduce grain quality during storage by feeding. This leads to a loss in weight, nutritional value, the viability of seeds, and they contaminate the grains and cause odor change, growth of mold, and heat damage. All these reduce grain quality and make them unsuitable for human food or animal feed [41].

Rajendran [42] listed more than 600 species of beetle pests, 70 species of moths, and about 355 species of mites causing quantitative and qualitative losses of stored products (Table 1). The particular insect pest species present in the storage depends on several factors; among them, grain type is important. All cereal grains and many stored legumes are infested by pests larvae either feeding or developing inside the kernel or outside intact kernels. The internal-feeding insects have been referred to historically as primary pests, while those feeding outside the kernels on broken and fine material have been referred to as secondary pests. Some of the most serious destructive insect pests of wheat are internal feeders, such as the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), which lays eggs outside the kernel and the larvae bore into the kernel to complete development to the adult stage. In contrast, rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), lays eggs directly inside the kernel. The red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Laemophloeidae), the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae), are the most

Table 1: Important stored grain insect pests in most African countries.

Common name	Scientific name	Major commodity attacked
Beetles		
Rice weevil	*Sitophilus oryzae* (Linnaeus)	Wheat, rice
Maize weevil	*Sitophilus zeamais* (Motsch.)	Maize
Granary weevil	*Sitophilus granarius* (Linnaeus)	Wheat
Khapra beetle	*Trogoderma granarium* (Everts)	Wheat, rice
Lesser grain borer	*Rhyzopertha dominica* (Fabricius)	Wheat, paddy
Larger grain borer	*Prostephanus truncatus* (Horn)	Maize
Red flour beetle	*Tribolium castaneum* (Herbst)	Rice
Confused flour beetle	*Tribolium confusum* (Jacquelin du Val)	Rice
Long-headed flour beetle	*Latheticus oryzae* (Waterhouse)	Rice
Sawtoothed grain beetle	*Oryzaephilus surinamensis* (Linnaeus)	Rice
Grain beetles	*Cryptolestes* spp.	Rice
Moths		
Angoumois grain moth	*Sitotroga cerealella* (Olivier)	Paddy
Almond moth	*Ephestia cautella* (Walker)	Wheat, rice
Indian meal moth	*Plodia interpunctella* (Hübner)	Wheat
Psocids		
Booklice	*Liposcelis* spp.	Rice

Source: Rajendran [42].

common external-feeding pests of wheat. The maize weevil, *Sitophilus zeamais* Motschulsky, and the angoumois grain moth, *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechiidae), are internal feeder insects, which are most commonly found in shelled corn (maize); external-feeding pests include *C. ferrugineus*; the flat grain beetle, *C. pusillus* (Sch ̈ onherr); *O. surinamensis*. Major internal-feeding pests of rice are *R. dominica*, *S. oryzae*, and *S. cerealella* [42].

Abass et al. [4] argued that among all the biotic factors, insect pests are considered the most important groups that cause huge postharvest losses in the grains ranging from 30 to 40%. Abass et al. [4] reported that after six months of maize storage, larger grain borer (*Prostephanus truncates*) was responsible for more than half (56.7%) of the storage losses, followed by losses due to grain weevil (*Sitophilus granarius)* and lesser grain borer *(Rhyzopertha dominica)*.

4. Most Commonly Used Botanicals against Stored Grain Insect Pests

Botanicals possess active ingredients that act on storage pests. Many spices possess insecticidal activities, especially in the form of essential oils (Table 2) [71]. Spices are used to flavor foods and/or protect stored products from pests. Traditionally, slices of dried spices or ground spices are mixed with stored foods, but recently their extracts or oils have given encouraging results. These compounds do not leave toxic residues in the environment, are not toxic to mammals, and have medicinal properties for humans [72–74]. The characteristic flavors and odors derived from the volatile oils of spices are known to have various effects on insect pests, including stored grain insect pests [75]. They can be used sustainably to replace synthetic pesticides [76].

Other plants are also used to combat stored grain pests (Table 3). The medicinal plants, *Artemisia vulgaris* L., *Artemisia aucheri* Boiss., *Artemisia scoparia* Waldst. et Kit., and *Artemisia sieberi* Besser, repel or poison *Tribolium castaneum* (Herbst) [123, 124]. Essential oils of *Rosmarinus officinale* L. (Rosemary) act against *Sitophilus oryzae* L. and *T. castaneum* [125]. *Mentha piperita* L. and *Mentha arvensis* L. have fumigant activity against *T. castaneum* [123, 125].

Still, other plants (other than spices and medicinal plants) act against storage insect pests (Table 3). Prakash and Rao [126] reported research results of 160 plant species against major insects of stored products, e.g., the neem tree, *Azadirachta indica* [127, 128]. According to Derbalah [129], *Cassia senna* L., *Caesalpinia gilliesii* Hook, *Chrysanthemum frutescens* L., *Thespesia populnea* var. *acutiloba* Baker, *Bauhinia purpurea* L., *Euonymus japonicus* L., *and Cassia fistula* L. had good efficacy against *T. granarium; C. senna* was the most potent plant extract against *T. granarium*. Abdullahi [130] revealed that *Vitellaria paradoxa* has great potential against pulse beetle *Callosobruchus maculates*. The ethanol extract of bitter gourd, karanja, and urmoi protected wheat grains up to 30 days, with no side effects of seed viability after three months of treatment [131]. Lime peel oil effectively protected maize against weevil *Sitophilus zeamais* [130]; the powder (*Curcuma longa* L.) affected the normal physiology of the insects [132].

5. Nature of Botanical Pesticides and Their Mode of Action

5.1. Nature of Botanical Pesticides. Botanicals are products from plants valued for their pesticidal, medicinal, or therapeutic properties. These natural pesticides are renewable and could be prepared as fresh dried products, liquid extracts, powders, cakes, or mesh bags. In many countries, farmers have no access to find convectional insecticides easily and have been using botanicals successfully for protecting their crops against insect pests, nematode, fungal, and bacterial diseases either on the field or in the store.

Table 2: Common spices used in the management of stored grain insect pests.

Common name	Scientific name	Major bioactive compounds	Target insect species	References
Ginger	*Zingiber officinale* Roscoe	Shogaols, paradols, and zingerone	*Tribolium castaneum* (Herbst); *Ephestia kuehniella* (Zell.) *Plodia interpunctella* (Hübner)	[43–46]
Turmeric	Curcuma longa L.	Curcumin, demethoxycurcumin, and curcuminoid	Rhyzopertha dominica (Fabricius) (lesser grain borer), Sitophilus oryzae (L.), and Tribolium castaneum (Herbst)	[47–49]
Black pepper	*Piper nigrum* L.	Piperine, piperidines, and pyrrolidines	Tribolium castaneum (Herbst)	[50–52]
Black cumin	Nigella sativa L.	Thymoquinone, dithymoquinone, and thymohydroquinone	Tribolium castaneum (Herbst)	[53, 54]
Caraway	*Carum carvi* L.	(R)-carvone and D-limonene	*Sitophilus zeamais* (Motschulsky) and *Tribolium castaneum* (Herbst)	[55, 56]
Clove	*Syzygium aromaticum* L.	2-Methoxy-4-(2-propenyl)-phenol and trans-caryophyllene	Rhyzopertha dominica (Fabricius) *Sitophilus zeamais* (Motschulsky) *Tribolium castaneum* (Herbst)	[57–59]
Cinnamon	*Cinnamomum zeylanicum* Blume	Cinnamaldehyde and linalool	*Callosobruchus maculatus* (Fabricius) and *Sitophilus oryzae* L. *Callosobruchus chinensis (*L.)	[50, 60]
Cardamom	*Elettaria cardamomum* L.	1,8-Cineol, α-terpinyl acetate, terpinene, and fenchyl alcohol	*Sitophilus zeamais* (Motschulsky) Callosobruchus maculatus (Fabricius), Tribolium castaneum Herbst, and Ephestia kuehniella (Zeller)	[61, 62]
Rosemary	*Rosmarinus officinalis* L.	Camphor, α-thujone, 1,8-cineole	*Sitophilus granarius* (L.) Tribolium castaneum (Herbst)	[63–66]
Garlic	*Allium sativum* L.	Diallyl sulfide and diallyl disulfide	*Sitophilus zeamais* (Motschulsky) *Tribolium castaneum* (Herbst)	[49, 50, 67]
Greater Galangal	*Alpinia galanga* L.		*Sitophilus zeamais* (Motschulsky) *Tribolium castaneum* (Herbst) *Callosobruchus chinensis* (L.)	[54, 68–70]

Several scientists and farmers reported the usage of crude or formulated bioactive botanicals against insect pests [133–135].

Several dozens of plant insecticides are used worldwide [136], based on various extracts, especially of the families Rutaceae, Lamiaceae, Meliaceae, Asteraceae, Annonaceae, Malvaceae, and Labiatae. Mwine et al. [137] reported that thirty-four species belonging to eighteen families are used in traditional agricultural practices for pest control in Southern Uganda. Chandrakant et al. [138] reported 250,000 higher plants species (comprising angiosperms and gymnosperms); out of them, only 6% have been screened for biological activity. Pesticidal plants are widely distributed across many countries in the world. Sola et al. [139] listed a collection of pesticidal plants obtained from sub-Saharan African countries (Ghana, Kenya, Malawi, Tanzania, Zambia, and Zimbabwe). Accordingly, 59 plant species have been evaluated for pest control and documented, yet only a few are being used in more than three countries [139]. Similarly, [140] recorded important botanicals to control or suppress various storage insect pests like *Sitophilus oryzae, S. zeamais, Callosobruchus chinensis, C. maculates, Tribolium castaneum, Rhyzopertha dominica, and Trogoderma granarium* Everts. Mohammed [141] reported five important plant species used by farmers to protect insect pests, including *Capsicum annuum* L., *Aloe vera* Miller, *Croton macrostachyus* Hochst, *Boswellia papyrifera, Kleinia* spp., *Vernonia amygdalina* Del., *Euphorbia* spp., *and Carissa schimperi* A. DC. In the Eastern part of Ethiopia. Tsegay et al. [142] made a survey in the Amhara Regional State of Ethiopia and documented 31 plant species used by farmers to prevent pest attacks during stacking of their crops. The plants belong to 21 families, with *Asteraceae* (five species), *Fabaceae* (four species), *Rosaceae* (three species), and *Cupressaceae* (two species) being the most represented plant families as botanical pesticides.

From the chemical point of view, botanical insecticides can be classified into essential oils, alkaloids, flavonoids, glycosides, esters, and fatty acids. Some of the synthetic pesticides are also derived from natural compounds as biopesticides. Third-generation pest control agents, reduced risk of pesticides, and bio-based pesticides are other terms used interchangeably with biopesticides [143]. The desirable qualities are as follows: less toxic nontarget organisms, easily degradable, easy to handle, ecofriendly, and target-specific [144, 145]. The major commercially used botanical pesticides in agricultural pest management belong to four major categories: (i) rotenone; (ii) pyrethrum; (iii) neem-based pesticides; and (iv) plant essential oils.

Table 3: List of some plant species with insecticidal property and their mode of activity.

Plant species	Major constituents of the active ingredient	Target insect species	Mode of activity	References
Acorus calamus (L.)	*β*-Asarone	*Sitophilus zeamais* (Motsch.)	Fumigation	[77]
Acorus gramineus (Ogon)	Z-asarone	*Sitophilus zeamais* (Motsch.)	Contact	[78]
Aegle marmelos (L.)	Limonene, A pinene, sabinene, ocimene, and P-caryophyllene	*Callosobruchus chinensis* (L.), *Rhyzopertha dominica* (Fabricius), *Sitophilus oryzae* (L.), and *Tribolium castaneum* (Herbst)	Fumigation	[79]
Allium sativum L. (Garlic)	Methyl allyl disulfide and diallyl trisulfide	*Sitophilus zeamais* (Motsch.) and *Tribolium castaneum* (Herbst)	Fumigation	[80]
Alpinia conchigera (Griff)	1,8-Cineole, *β*-pinene, *α*-pinene, *β*-sesquiphellandrene, and a-terpineol, 1,8-cineole	*Sitophilus zeamais* (Motsch.) *and Tribolium castaneum* (Herbst)	Fumigation	[66]
Annona reticulate (L.) *Polygonum hydropiper* (L.)	Anonaine	*Callosobruchus chinensis* (Linnaeus)	Contact	[81]
Azadirachta indica (neem seed)	di-*n*-propyl disulfide	*Tribolium castaneum* *Sitophilus* oryzae (Linnaeus)	Contact/fumigant	[82]
Azilia eryngioides (Pau)	A-Pinene and bornyl acetate	*Sitophilus granaries* (L.) *Tribolium castaneum* (Herbst)	Fumigation	[83]
Calpurnia aurea (Ait.) Benth	Tannins, flavonoids, terpenoids, saponins, steroids, glycosides, and alkaloids	*Sitophilus zeamais* (Motsch.)	Contact	[84, 85]
Carum carvi (Linnaeus)	Carvone and limonene	*Sitophilus oryzae* and *Rhyzopertha dominica* (Fabricius)	Contact/fumigant	[86]
Chamaecyparis obtuse (Endl.)	(+)-Limonene, myrcene *α*-phellandrene, *α*-pinene, bornyl acetate	*Sitophilus oryzae* (Linnaeus) Callosobruchus chinensis (L.)	Contact	[28]
Chenopodium ambrosioides (Lineu)	(*Z*)-ascaridole, 2-carene, rho-cymene, isoascaridole, and alphaterpinene	*Sitophilus zeamais* (Motsch.)	Fumigation	[87]
Cinnamomum aromaticum (Nees)	Cinnamaldehyde	*Tribolium castaneum* (Herbst) *and Sitophilus zeamais* (Motsch.)	Contact/fumigant	[88]
Cinnamomum camphora (Kapur)	D-camphor,1,8-cineole, *α*-terpineol,3-methyl-2-butenoic acid, oct-3-en-2-yl ester, safrole, linalool	*Tribolium castaneum* (Herbst), *Lasioderma serricorne* (Fabricius)	Contact, fumigant	[89–92]
Citrus aurantium (L.)	Limonene	*Rhyzopertha dominica* (Fabricius) *and Tribolium castaneum* (Herbst)	Contact	[93]
Eruca sativa (Mill)	Chlorpyrifos	*Rhizopertha dominica* (Fabricius)	DNA damage	[94]
Coriander *sativum* (L.)	Eugenol, isoeugenol and methyl eugenol, linalool, camphor	*Callosobruchus maculates* (Fabricius) *Sitophilus zeamais* (Motsch.) *Tribolium castaneum* (Herbst) Cryptolestes pusillus (Schönherr) and *Rhyzopertha dominica* (Fabricius)	Contact and fumigation	[95, 96]
Curcuma longa (L.) (Turmeric)	Ar-turmerone coumaric acid	*Sitophilus zeamais* (Motsch.)	Contact	[24, 97]
Curcuma zedoaria (L.)	Camphor a-zingiberene, camphene, a-curcumene, and isoborneol	*Tribolium castaneum* (Herbst)	Fumigation	[66]
Elettaria cardamomum (L.)	A-terpinyl acetate 1,8-Cineole Linalyl acetate and sabinene	*Sitophilus zeamais* (Motsch.) Callosobruchus maculatus (Fabricius), Tribolium castaneum (Herbst), and Ephestia kuehniella (Zeller)	Contact and fumigation	[61, 80, 91]
Eucalyptus spp.	1,8 Cineole	*Sitophilus oryzae* (L.)	Fumigant	[98]

Table 3: Continued.

Plant species	Major constituents of the active ingredient	Target insect species	Mode of activity	References
Eucalyptus (Eucalyptus globulus Labiil*)*	1–8-Cineole	*Tribolium castaneum* (Herbst) and *Sitophilus oryzae* (Linnaeus)	Repellent	[99, 100]
Evodia lenticellata (Huang)	Linalool, β-pinene, 3-carene, caryophyllene oxide, and β-caryophyllene (7.9%)	*Tribolium castaneum* (Herbst) Lasioderma serricorne (Fabricius) and Liposcelis bostrychophila (Badonnel)	Fumigation contact and repellent	[101]
Foeniculum vulgare (Mill)	Estragole, (+)-fenchone and (*E*)-anethole	*Sitophilus oryzae* (Linnaeus), *Callosobruchus chinensis* (L.), and *Lasioderma serricorne* (Fabricius)	Contact and fumigation	[102]
Lantana camara (L.)	β-Caryophyllene α-humulene cis-Caryophyllene	*Sitophilus zeamais* (Motsch.) *Sitophilus granarius* *Callosobruchus maculatus* (Fabricius)	Contact/ fumigation and repellent	[103–106]
Lavandula angustifolia (Mill)	Linalool, 1,8-cineole, borneol, terpinen-4-ol	*Sitophilus granarius* (L.)	Contact/ fumigation and repellent	[107]
Lippia alba (Mill)	Carvone chemotypes LA-13 and LA-57	*Sitophilus zeamais* (Motsch.) and *Tribolium castaneum* (Herbst)	Contact/and repellent	[108, 109]
Lonchocarpus sp.	Rotenone	*Sitophilus oryzae* (L.)	Contact; stomach poison	[110]
Mentha suaveolens subsp. Timija (Briq.)	Menthone and pulegone	*Tribolium castaneum* (Herbst)	Contact	[111]
Millettia ferruginea (Hochst.)	Flavonoids, rotenone isoflavonoids, chalcones, terpenoids Tannins, saponins, steroids, glycosides, and alkaloids	*Sitophilus zeamais* (Motsch.)	Contact	[85, 112, 113]
Mentha piperita (L.)	Menthol, L-menthone, isomenthol, and limonene	*Tribolium castaneum* (Herbst), *Lasioderma serricorne* (Fabricius), and *Liposcelis bostrychophila* (Badonnel)	Fumigation, contact, and repellent activity	[114]
Ocimum basilicum (Labiatae)	Eugenol	*Tribolium castaneum* (Herbst) *Sitophilus oryzae* (Linnaeus) *Callosobruchus maculatus* (Fabricius)	Repellent/ fumigation	[99, 100, 115]
Ocimum canum (Sims)	Linalool	Sitophilus oryzae (Linnaeus)	Repellent	[116]
Ocimum kilimandscharicum (Labiatae)	Camphor	*Sitophilus oryzae* (L.)	Repellent	[117]
Ricinus communis (L.)	Ricin	*Plutella xylostella* (L.)	Contact or feeding	[118]
Securidaca longepedunculata (Fresen.)	Methyl salicylate	*Sitophilus zeamais* (Motsch.), *Rhyzopertha dominica* (Fabricius), and *Prostephanus truncates* (Horn)	Contact and repellent	[119]
Tephrosia vogelii (Hook)	Rotenoids	*Sitophilus zeamais*	Contact	[105, 120]
Thujopsis dolabrata (Sieb)	Carvacrol	*Sitophilus oryzae* (Linnaeus), *Callosobruchus chinensis* (L.)	Contact; fumigant	[28]
Gnidia kraussiana (Meisn)	Terpenes	Callosobruchus maculatus (Fabricius)	Contact and repellent	[121, 122]

5.1.1. Rotenone. As an insecticide, rotenone has been used for more than 150 years, but its use as a fish poison dates back even further [146]. Rotenone is one of several isoflavonoids produced in the roots or rhizomes of the tropical legumes *Derris* spp., like *Lonchocarpus* and *Tephrosia.* Basically, it is a broad-spectrum botanical insecticide used to control aphids, trips, and suckers with some acaricidal properties. In other cases, it could be used for water body management to eradicate fish. Because of its natural origin, the use of rotenone as an insecticide has been allowed in the last two decades in organic crop production [80, 147]. However, the current study of Zhang et al. [148] showed that due to its link with Parkinson's disease, the use of rotenone was banned in many developed countries. In agreement with this study, [149] described the neurotoxicity nature of rotenone on mice indicating that rotenone has a hazardous effect on animals.

5.1.2. Pyrethrum. Pyrethrum refers to the oleoresin extracted from the dried flowers of the pyrethrum daisy, *Tanacetum cinerariaefolium* (Asteraceae). The flowers are ground to a powder and then extracted with hexane or a similar nonpolar solvent; removal of the solvent yields an orange-colored liquid that contains the ingredients of the active principle [150, 151]. These are three esters of chrysanthemic acid and three esters of pyrethric acid. Among the six esters, those incorporating the alcohol pyrethrolone, namely, pyrethrins I and II, are the most abundant and account for most of the insecticidal activity. Technical grade pyrethrum, the resin used in formulating commercial insecticides, typically contains 20% to 25% pyrethrins [150].

5.1.3. Neem-Based Pesticides. Two types of botanical insecticides can be obtained from seeds of the Indian neem tree, *Azadirachta indica* (Meliaceae) [152]. Neem oil, obtained by cold-pressing seeds, can be effective against insects with soft body and mites but is also useful in managing phytopathogens. The disulfides in the oil are responsible for the bioactivity against pests and fungi. The medium-polarity extracts of the seed residue after oil removal contain the complex triterpene azadirachtin, which possesses a higher value than neem oil. Neem seed contains more than a dozen azadirachtin analogs, but the major form is azadirachtin and the remaining minor analogs likely contribute little to the overall efficacy of the extract. Seed extracts include considerable quantities of other triterpenoids, notably salannin, nimbin, and derivatives. The role of these natural substances has been controversial, but most evidence points to azadirachtin as the most important active principle [153]. Neem seeds typically contain 0.2% to 0.6% azadirachtin by weight; by concentration processes, the active ingredient can be prepared to the level of 10% to 50% in the technical grade material used to produce commercial products.

5.1.4. Plant Essential Oils. Steam distillation of aromatic plants yields essential oils, long used as fragrances and flavorings in the perfume and food industries, respectively, and more recently for aromatherapy and as herbal medicines [154, 155]. Plant essential oils are produced commercially from several botanical sources, many of which are members of the mint family (Lamiaceae). The oils are generally composed of complex mixtures of monoterpenes, biogenetically related phenols, and sesquiterpenes. Examples include 1, 8-cineole, the major constituent of oils from rosemary (*Rosmarinus officinale* L.) and eucalyptus (*Eucalyptus globulus* Labill.); eugenol from clove oil (*Syzygium aromaticum* L.); thymol from garden thyme (*Thymus vulgaris* L.); menthol from various species of mint (*Mentha* species) [156]. A number of plants have been traditionally used to protect stored commodities, especially in the Mediterranean region and in southern Asia. Still, interest in the oils was renewed with the emerging demonstration of their fumigant and contact insecticidal activities to a wide range of pests in the 1990s [157]. The rapid action against some pests is due to the neurotoxic action, and there is evidence for interference with the neuromodulator octopamine [158, 159] by some oils and with GABA-gated chloride channels by others [160].

5.2. Botanical Pesticides and Their Mode of Action. Mode of action refers to the specific biochemical interaction through which a pesticide shows its effect. Basically, the mode of action includes the effect on certain specific enzymes, proteins, and a biological system [161, 162]. It is the way in which it causes physiological disruption at its target site. Therefore, insecticide class, target site, and mode of action are highly interconnected concepts. Understanding the mode of action is an essential part for scientists to advance the quality and sustainability of a product. Researchers were reported that understanding the action of pesticides is multifunctional, and they normally target different metabolic systems. Singh and Chengala [163] summarized major groups of botanical pesticides and their mode of action.

Mordue [86] stated the following basic modes of action of azadirachtin in insects:

(i) The blockage of input receptors for phagostimulants leads to inhibiting the feeding process or the stimulation of deterrent receptor cells, or both.

(ii) Growth inhibition by the blockage of a morphogenetic peptide hormone affects ecdysteroid and juvenile hormone titers.

(iii) Direct detrimental and histopathological effects on insect muscles, fat body, and gut cuticular epithelial cells. Azadirachtin has also demonstrated its negative effects by reducing hemocyte count, degenerating organelles, and destroying plasma membranes [164].

Similarly, [165] revealed the impact of neem extracts on digestive enzymes, such as amylase, protease, and lipase. Shaaya et al. [166] summarized the mode of activity of botanicals pesticides in six general mechanisms as follows: (1) acting through respiration like a fumigant; (2) acting through contact or digestion as a contact or oral insecticide; (3) preventing reproduction (also causing sterilization); (4)

antifeeding effect; (5) repulsive effect or change insect behavior; (6) having a combination of all given. IRAC [167] produced detailed information regarding the mode of action of insecticides and the target sites.

6. Recent Development and Status of Botanical Insecticides against Stored Grain Pests

During the past few decades, the interest in using plant-based pesticides has increased, chiefly the natural origin with low mammalian toxicity [168]. In different parts of the world, attention has been paid to the exploitation of plant products as novel substances in plant protection. Because of low phytotoxicity, easy biodegradability, and the stimulatory nature of host metabolism, plant products possess the potential value in pest management [169]. Higher plants contain a wide spectrum of secondary metabolites such as phenols, flavonoids, quinones, tannins, essential oils, alkaloids, saponins, and sterols. Such plant-derived chemicals may be exploited for their different biological properties. In the context of agricultural pest management, botanical insecticides are best suited for use in organic food production in industrialized countries but can play a much greater role in the production and postharvest protection of the food in developing countries [36].

Accordingly, the use of green pesticides, particularly for stored grain pests, is being recommended globally, and the use of essential oils seems to be the best choice. Studies have shown that essential oils are readily biodegradable and less detrimental to nontarget organisms than synthetic pesticides [170]. The application of plant products, especially essential oils, is a very attractive method for controlling postharvest diseases and pests. The production of essential oils by plants is believed to be predominantly a defense mechanism against pathogens and pests [171].

Companies specialized in the production of botanical pesticides strive to improve the formulations, stabilization of the extracts, and consistent chemical pattern to answer the quality standards of the marketed products. According to Kleeberg and Ruch [172], the standardization of neem seed extracts, which show a large variation of azadirachtin content, is one of the keys to enhancing neem product commercialization. These requirements could be resolved with the marketing of synthesized molecules identical in every point to the natural molecule (i.e., organoleptic properties, degree of purity, and absence of residual solvents). Recently, several new substances have been reported in the literature as promising compounds for use as biopesticides [173], but more field research is necessary for assessing their efficacy on specific pest problems under diverse cropping systems.

Pest management products from plants are also an important segment of the biopesticide market. Isman [36] discussed botanical insecticides from a global perspective as in 1980, <2% of all journal papers published were on botanicals insecticides, but the number exceeded 21% in 2011. There has been an explosive growth in reported studies of the insecticidal activity of plant essential oils, but this activity has not been reflected in the increased commercialization of botanical insecticides, at least not in the major North American and European markets. Much interest in botanical insecticides has come from China and other Asian nations, Latin America, and Africa, perhaps due to the potentially lower cost, local sourcing, and relatively lower mammalian toxicity. Particularly, those plant-derived extracts from local farmers are relatively cheaper in preparation and more convenient in application with lower cost due to the locally grown plants for local use compared to the use of synthetic ones [139, 174]. Globally, the demand for natural pesticides is growing [175, 176] due to the increasing interest in organically produced safe food. However, commercially available botanical insecticides have been largely limited to pyrethroids and neem, to a lesser extent, limonene, chenopodium, capsicum oleoresin, and garlic oils [176].

Significant numbers of studies have been reported regarding the use of botanical biopesticides against storage and field crop pests. The following have been reported: neem leaves against a variety of pests [177]; *Clerodendrum serratum* L. leaf extracts and powdered leaves and leaf extracts of *Olax zeylanica* Wall., against the rice weevil (*S. oryzae* L) [178]; *Cichorium intybus* L, *Melilotus parviflora* L, *Chenopodium album* L against *Trogoderma granarium* Everts [179]; methanolic extracts of medicinal plants against wheat pest *Tribolium castaneum* Herbst [180]; *Phthorimaea operculella* Zeller against the potato tuber moth [181]. Other essential oils from *Eucalyptus nicholii* Maiden and Blakely, *Eucalyptus codonocarpa* Blakely and Mckie, *Eucalyptus blakelyi* Maiden, *Callistemon sieberi* F. Muel., *Melaleuca fulgens* R. Br., and *Melaleuca armillaris* Sm. are used against *S. oryzae*, *T. castaneum* Herbst and *Rhyzopertha dominica* Fabricius [182], *N. tabacum*, *T. vogelii*, *Ocimum gratissimum* L., and *Crassocephalum crepidioides* S. Moore against the bean weevil [183].

Obeng-Ofori et al. [184] evaluated the bioactivity of materials from the leaves of *Ocimum kilimandscharicum* Labiatae against the beetles, *Sitophilus granarius* L., *S. zeamais* Motsch., *Tribolium castaneum* Herbst, and *Prostephanus truncatus* Horn. All plant pesticides reported up to 100% mortality after 24 hr exposure of adult insects to dried leaves and essential oil extract of the plant. Bekele [112] also evaluated the toxicity of different plant parts of *Millettia ferruginea* (Hochst.) against *S. zeamais* in maize seeds. Seed powder applied at 10%w/w to maize seeds was toxic to the weevil and caused a significant reduction in reproduction.

7. Constraints on the Use of Botanical Pesticides against Stored Grain Insect Pests

7.1. Lack of Appropriate Plant Material. Many perspective plants are extremely difficult to grow to provide a sufficient amount of high-quality material suitable for isolating active substances. Therefore, most commercial products are manufactured only from a few plant species that provide sufficiently high yields [185, 186].

7.2. Lengthy and Time-Consuming Processing. The utilization of organic pesticides, for example, botanicals, has different constraints. Anjorin [187] reported that the constraints of using botanical pesticides in terms of production are the laborious and time-consuming processes of collecting, drying, and grinding plant parts and using crude and household materials, like pestle, mortar, and containers, which are often contaminated with stained, hard flavors.

7.3. Insufficient Modern Processing Facilities. The other constraint is inadequate modern processing facilities [188], which are necessary for the efficient isolation, purification, and compounding of natural products into pesticides. The processes of simplification and purification of the active ingredients are often slow and cumbersome and may lead to loss of activity. Dayan et al. [24] found that it is often difficult to standardize their dosages due to variation in their diverse growing conditions, varietal differences and age of sample at harvest, extraction methods, and storage conditions.

7.4. Toxicity of Some Plant-Derived Compounds. Botanical pesticides are not totally safe for humans. In general, their essential oils and major constituents are relatively nontoxic to mammals, with acute oral LD_{50} values in rodents ranging from 800 to 3,000 $mg{\cdot}kg^{-1}$ for pure compounds and >5,000 $mg{\cdot}kg^{-1}$ for formulated products [189]. Despite their safety, some essential oils can be irritating to the skin [190]. Although the short residual activity is considered a benefit for the environment, multiple applications are required. The repeated use of botanical pesticides also leads to resistance. Some plant-derived compounds, particularly rotenone and nicotine, are more toxic to humans than many common synthetic insecticides. However, their limited persistence in the environment helps to minimize their adverse effects [191].

7.5. Lack of Complete Profile of Botanical Pesticides. Another major obstacle in promoting botanical pesticides as an alternative to chemical pesticides is the lack of understanding of complete action and clear chemical profile of the pesticides. The relative immaturity of the policy network, limited resources, and capabilities and lack of trust between regulators and producers are some of the serious problems. A better understanding of biopesticides mode of action and regulatory issues adoption may help further to raise their profile among the public and policymakers to realize their contributions to sustainability. Since environmental safety is a global concern, awareness among the farmers, manufacturers, government agencies, policymakers, and the common people is needed to switch over to botanical pesticides for the pest management requirements [192].

Although various essential oils have been screened for their pesticidal activity against various pests, detailed studies on their antifungal, insecticidal, repellency, oviposition, ovicidal, antiaflatoxigenic activities, phytochemistry, safety, and limit profile have not been conducted scientifically. Therefore, it is an urgent need to assess the pesticidal property of different essential oils, and detailed *in vitro* and *in vivo* investigations are required to recommend their practical application [193].

7.6. Problems in Regular Global Registration of Botanical Pesticides. Natural plant products are not easily patented, a corporation that sponsors the toxicological testing required to obtain registrations for usage faces competition, which has been a stumbling block in their successful introduction as pest control technology advances. Hence, although some ingredients are now commercially available as botanical pesticides, the registration for direct application on a given stored commodity requires attention and further considerations in conjunction with a food safety-oriented strategy [194]. Unless it is proven that these compounds are safe and do not affect food properties, the consumers' demand for residue-free food is not always compatible with the use of botanicals in stored product protection. This made the registration process of botanical products difficult.

8. Conclusion

The use of plant secondary metabolites synthesized by some plant species as part of their natural self-defense against stored product insect pests seems to be an excellent alternative. Botanical pesticides (essential oils, flavonoids, alkaloids, glycosides, esters, and fatty acids) have various chemical properties and modes of action and affect insects in different ways, namely, repellents, feeding deterrents/antifeedants, toxicants, growth retardants, chemosterilants, and attractants. Thus, it is preferable to use botanical insecticides instead of synthetic insecticides and these botanical insecticides are recognized by organic crop producers in industrialized countries.

It is also important to raise awareness among farmers to use the botanical products as pesticides. In some areas in particular, high attention is now paid to raise awareness especially in developing countries where long-term projects are being designed and aimed at educating growers about the basic skills of manufacturing botanical pesticides.

Based on the number of scientific studies focused on the research of plant substances with insecticidal effects, it seems that commercial botanical insecticides should occupy an important position in the market. However, a better understanding of their mode of action, effects, and information related to regulatory issues is needed for their adoption. The scientific standardization may help further to raise their profile among the public and policymakers and hence enable them to realize their contributions to sustainability. Therefore, it is recommended to use botanical insecticides and conducting research to find new sources of botanical insecticides is very crucial.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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