

Review Article

Botanicals as Grain Protectants

Yallappa Rajashekar,¹ Nandagopal Bakthavatsalam,¹ and Thimmappa Shivanandappa²

¹ National Bureau of Agriculturally Important Insects, P. Bag No:2491, H.A. Farm Post, Bellary Road, Karnataka, Bangalore 560 024, India

² Department of Zoology, University of Mysore, Manasagangotri, Karnataka, Mysore 560007, India

Correspondence should be addressed to Yallappa Rajashekar, rajacftri@yahoo.co.in

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Prevention of food losses during postharvest storage is of paramount economic importance. Integrated pest management is now a widely accepted strategy in pest control including postharvest infestation control which involves the use of chemical (contact/residual) insecticides along with fumigants. The use of synthetic chemical insecticides is either not permitted or used restrictively because of the residue problem and health risks to consumers. In view of the above, there is a need for plants that may provide potential alternatives to the currently used insect control agents as they constitute a rich source of bioactive molecules. Available literature indicates that plant could be source for new insecticides. Therefore, there is a great potential for a plant-derived insecticidal compounds. This paper focuses on the current state of the botanical insecticides as grain protectants and its mode of action.

1. Introduction

Food grain losses due to insect infestation during storage are a serious problem, particularly in the developing countries [1, 2]. Losses caused by insects include not only the direct consumption of kernels, but also accumulation of exuviae, webbing, and cadavers. High levels of the insect detritus may result in grain that is unfit for human consumption and loss of the food commodities, both, in terms of quality and quantity. Insect infestation-induced changes in the storage environment may cause warm moist “hotspots” that provide suitable conditions for storage fungi that cause further losses. It is estimated that more than 20,000 species of field and storage pests destroy approximately one-third of the world's food production, valued annually at more than \$100 billion among which the highest losses (43%) occurring in the developing world [3, 4]. The quantitative and qualitative damage to stored grains and grain product from the insect pests may amount to 20–30% in the tropical zone and 5–10% in the temperate zone [5, 6]. Food grain production in India has reached 250 million tonnes in the year 2010-2011, in which nearly 20–25% food grains are damaged by stored

grain insect pests [7, 8]. The efficient control and removal of stored grain pests from food commodities has long been the goal of entomologists throughout the world.

The major pests of stored grain and pulses of the Indian subcontinent are classified in to two groups, namely, primary pests: those which are capable of penetrating and infesting intact kernel of grain and have immature stages develop within kernel of grain and secondary pests which cannot infest the whole grain but feed on as broken kernels, debris, high moisture weed seeds, and grain damaged by primary pests. In general, the immature stages of the secondary pest species are found external to the grain. It is often thought that secondary invaders cannot initiate infestation. The important primary pests are the rice weevil, *Sitophilus oryzae* (L.), granary weevil, *Sitophilus granaries* (L.), (Coleoptera: Curculionidae), lesser grain borer, *Rhyzopertha dominica* (F.), (Coleoptera: Bostrichidae), Khapra beetle, *Trogoderma granarium* (Everts), (Coleoptera: Dermestidae), and the pulse beetle *Callosobruchus chinensis* (L.) (Coleoptera: Bruchidae). The secondary pests are rust-red flour beetle, *Tribolium castaneum* (Herbst), (Coleoptera: Tenebrionidae), rusty grain beetle, *Cryptolestes ferrugineus* (L.), (Coleoptera: Cucujidae),

sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.), (Coleoptera: Silvanidae), mites, (Acarina: Tetranychidae) *Liposcelis corrodens*, and (Psocoptera: Liposcelidae).

2. Infestation Control by Pesticides and Their Side Effects

Since the 1950s, synthetic insecticides have been used extensively in grain facilities to control stored product insect pests. Fumigants such as methyl bromide, phosphine, cyanogens, ethyl formate, or sulfuryl fluoride rapidly kill all life stages of stored product insects in a commodity or in a storage structure. Fumigation is still one of the most effective methods for the prevention of stored product losses from insect pests. But pests develop resistance, not stored products were showing a slow upsurge in fumigation resistance [9]. Resistance to phosphine is so high in Australia and India, it may cause control failures [10, 11]. Methyl bromide has been identified as a major contributor to ozone depletion [12] and has been banned in developed countries, and developing nations have committed to reducing the use by 20% in 2005 and phase out in 2015. Contact insecticides such as malathion, chlorpyrifos, or deltamethrin are sprayed directly on grain or storage structure for protection from infestation for several months. The incidence of insecticide resistance is a growing problem in stored-product protection. Resistance to one or more insecticides has been reported in at least 500 species of insects and mites [13].

Champ [14] reported that resistance to pesticides used to protect grain and other stored food stuffs is widespread and involves all groups of pesticides and most of the important pests. Some of the contact insecticides have become ineffective because of widespread resistance in insect population. Resistance to malathion is widespread in Canada, USA and Australia [15]. Stored product insects pests were found to be resistant against different insecticides including the cyclodienes, chlorpyrifos, cyanophos, carbamates, carbaryl, cypermethrin, dichlorodiphenyltrichloroethane, deltamethrin, diazinon, dichlorovos, ethylene bromide, ethyl formate organophosphates, permethrin, pyrethrins, and propoxur.

Although chemical insecticides are effective, their repeated use has led to residual toxicity, environmental pollution and an adverse effect on food besides side effect on humans [16, 17]. Their uninterrupted and indiscriminate use not only has led to the development of resistant strains but also accumulation of toxic residues on food grains used for human consumption that has led to the health hazards [18]. In view of all these problems, several insecticides have either been banned or restricted in their use.

3. Botanicals as Alternative to Synthetic Pesticides

The increasing serious problems of resistance and residue to pesticides and contamination of the biosphere associated with large-scale use of broad spectrum synthetic pesticides have led to the need for effective biodegradable pesticides

with greater selectivity. This awareness has created a world-wide interest in the development of alternative strategies, including the discovery of newer insecticides [19, 20]. However, newer insecticides will have to meet entirely different standards. They must be pest specific, nonphytotoxic, nontoxic to mammals, ecofriendly, less prone to pesticide resistance, relatively less expensive, and locally available [21]. This has led to re-examination of the century-old practices of protecting stored products using plant-derivatives, which have been known to resist insect attack [5, 22–24]. Plant derived materials are more readily biodegradable, less likely to contaminate the environment and may be less toxic to mammals. There are many examples of very toxic plant compounds. Therefore, today, researchers are seeking new classes of naturally occurring insecticides that might be compatible with newer pest control approaches [2, 25, 26].

Since ancient times, there have been efforts to protect harvest production against pests. The Egyptian and Indian farmers used to mix the stored with fire ashes [83, 84]. The ancient Romans used false hellebore (*Veratrum album*) as a rodenticide, the Chinese is credited with discovering the insecticidal properties of Derris species, whereas pyrethrum was used as an insecticide in Persia and China [4]. In many parts of the world, locally available plants are currently in wide use to protect stored products against damage caused by insect infestation [80, 85–87]. Indian farmers used neem leaves and seed for the control of stored grain pests [88]. In northern Cameroon, cowpeas are traditionally mixed with sieved ash after threshing and the mixture put into mud granaries or clay jars [89]. In eastern Africa, leaves of the wild shrub *Ocimum suave* and the cloves of *Eugenia aromatic* are traditionally used as stored grain protectants [90]. In Rwanda, farmers store edible beans in a traditional closed structure (imboho) and whole leaves of *Ocimum canum* are usually added to the stored foodstuff to prevent insect damage within these structures [75]. Owusu [91] suggested natural and cheaper methods for the control of stored product pests of cereals, with traditionally useful Ghanaian plant materials. In some south Asian countries, food grains such as rice or wheat are traditionally stored by mixing with 2% turmeric powder [92, 93]. The use of oils in stored-products pest control is also an ancient practice. Botanical insecticides such as pyrethrum, derris, nicotine, oil of citronella, and other plant extracts have been used for centuries [27, 94, 95]. More than 150 species of forest and roadside trees in India produce oilseeds, which have been mainly used for lighting, medicinal purposes, and also as insecticides from ancient times to early 20th century [96]. Turmeric, garlic, *Vitex negundo*, gliricidia, castor, *Aristolochia*, ginger, *Agave americana*, custard apple, *Datura*, *Calotropis*, *Ipomoea*, and coriander are some of the other widely used botanicals to control and repel crop pests [81, 97].

Talukder [5] has listed 43 plant species as insect repellents, 21 plants as insect feeding deterrents, 47 plants as insect toxicants, 37 plants as grain protectants, 27 plants as insect reproduction inhibitors, and 7 plants as insect growth and development inhibitors. Eighteen species showed insecticidal

potential, and antiovipositional properties against *Sitophilus oryzae* [98].

4. Classification of Botanical Insecticides

On the basis of physiological activities on insects, Jacobson [3] conventionally classified the plant components into 6 groups, namely, repellents, feeding deterrents/antifeedants, toxicants, growth retardants, chemosterilants, and attractants. Focus on the toxicants and grain protectants on activity of essential oil, extracts, and its constituents has sharpened since the 1980s.

4.1. Repellents. The repellents are desirable chemicals as they offer protection with minimal impact on the ecosystem, as they drive away the insect pest from the treated materials by stimulating olfactory or other receptors. Repellents from plant origins are considered safe in pest control; minimise pesticide residue; ensure safety of the people, food, and environment [1, 5, 99]. The plant extracts, powders, and essential oil from the different bioactive plants were reported as repellent against stored grain insect pests [1, 91, 100–102]. For example, the essential oil of *Artemisia annua* was found as repellent against *Tribolium castaneum* and *Callosobruchus maculatus* [103].

4.2. Antifeedants/Feeding Deterrents. Antifeedants, sometimes referred to as “feeding deterrents” are defined as chemicals that inhibit feeding or disrupt insect feeding by rendering the treated materials unattractive or unpalatable [104, 105]. Some naturally occurring antifeedants, which have been characterized, include glycosides of steroidal alkaloids, aromatic steroids, hydroxylated steroid meliantriol, triterpene hemiacetal, and others [3, 106]. Essential oil constituents such as thymol, citronellal and α -terpineol are effective as feeding deterrent against tobacco cutworm, *Spodoptera litura* synergism, or additive effects of combination of monoterpenoids from essential oils have been reported against *Spodoptera litura* larvae [107]. The screening of several medicinal herbs showed that root bark of *Dictamnus dasycarpus* possessed significant feeding deterrence against two stored-product insects [108].

4.3. Toxicants. Research on new toxicants of plant origin has not declined in recent years despite the increased research devoted to the discovery of synthetic insecticides [25]. Worldwide reports on plant derivatives showed that many plant products are toxic to stored product insects [6, 16, 27, 55, 82, 91, 109–114]. Talukder [32] listed the use of 43 plant species expressing toxicant effects of different species of stored-products insects. Pascual-Villalobos and Robledo [115] carried out screening of plant extracts from 50 different wild plant species of southeastern Spain for insecticidal activity towards *Tribolium castaneum* and reported that four species, namely, *Anabasis hispanica*, *Senecio lopezii*, *Bellardia trixago*, and *Asphodelus fistulosus* were found to be promising. Two major constituents of the essential oil of garlic, *Allium sativum*, methyl allyl disulfide and diallyl trisulfide were to

be potent toxicant and fumigants against *Sitophilus zeamais* and *Tribolium castaneum* [116]. Rahman [117] reported that nicotine, an active component of *Nicotiana tabacum*, is a strong organic poison which acts as a contact-stomach poison with insecticidal properties. This compound is, of course, very toxic to humans as well. The essential oil vapours distilled from anise, cumin, eucalyptus, oregano, and rosemary were also reported as fumigants and caused 100% mortality of the eggs of *Tribolium confusum* and *Ephestia kuehniella* [118]. Many species of the genus *Ocimum* oils, extracts, and their bioactive compounds have been reported to have insecticidal activities against various insect species [59, 119]. A list of many known toxicants from plant origin, reported as effective on stored-product insect-pest management, is given in Table 1.

4.4. Natural Grain Protectants. From very early times, plant materials have been used as natural protectants of stored grains. Worldwide reports indicate that when mixed with stored grains, leaf, bark, seed powder, or oil extracts of plants reduce oviposition rate and suppress adult emergence of stored product insects, and also reduce seed damage rates [25, 40, 46, 87, 119–122]. In 1989, Jacobson [123] noted that the most promising natural grain protectants were generally observed in the plant families, Annonaceae, Asteraceae, Canellaceae, Labiatae, Meliaceae, and Rutaceae.

The Indian neem plant is the most well-known example and its various parts, namely, leaves, crushed seeds, powdered fruits, oil, and so forth, have been used to protect stored grain from infestation [1, 124, 125]. The neem oil and kernel powder gave effective grain protection against stored grain insect pests like *Sitophilus oryzae*, *Tribolium castaneum*, *Rhyzopertha dominica*, and *Callosobruchus chinensis* at the rate of 1 to 2% kernel powder or oil [126]. The neem oil adhered to grain forms uniform coating around the grains against storage pests for a period of 180–330 days [127]. Yadava and Bhatnagar [128] reported that a dried leaves of *Azadirachta indica* have been mixed with stored grains for protection against insects. Azadirachtin is an active principle from the neem plant, which is an effective grain protectant against insect infestation [129]. Rajashekar et al. [7] reported that root powder extracts of *Decalepis hamiltonii* have been mixed with stored grains for protection against various stored grain insect pests. Eighteen species offered protection to wheat up to 9 months without affecting seed germination [98].

In parts of eastern Africa, leaves of some plants and allelochemicals including azadirachtin, nicotine, and rotenone have traditionally been used as grain protectants [5, 130]. The powders of *Rauwolfia serpentina*, *Acorus calamus*, and *Mesua ferrea* are used as a grain protectant against *Rhyzopertha dominica* [131]. In a survey in northern semiarid regions of Ghana only 16 plants were identified as being used as grain protectants [132]. In Africa, the grain protectant potential of different plant derivatives, including plant oils against major stored-product pests were also found to be very promising and reduced the risks associated with the use of insecticides [82, 121]. In northern Cameroon, the

TABLE 1: List of plant species reported to show insecticidal activity.

Plant species	Family	Plant part	References
<i>Acorus calamus</i>	Acoraceae	O, RO	[27]
<i>Allium sativum</i>	Alliaceae	P	[28]
<i>Annona squamosa</i>	Annonaceae	L	[29]
<i>Aphanamixis polystachya</i>	Meliaceae	SC, SE	[25]
<i>Azadirachta indica</i>	Meliaceae	O, SP, LP	[30]
<i>Baccharis salicifolia</i>	Asteraceae	O	[31]
<i>Bassia longifolia</i>	Sapotaceae	E	[5]
<i>Brassica</i> spp.	Cruciferae	L, ZE	[32]
<i>Cajanus cajan</i>	Fabaceae	O	[33]
<i>Calophyllum inophyllum</i>	Clusiaceae	O	[34]
<i>Calotropis procera</i>	Apocynaceae	LP	[35]
<i>Carum carvi</i>	Apiaceae	FE	[36]
<i>Cinnamomum aromaticum</i>	Lauraceae	B	[37]
<i>Citrus</i>	Rutaceae	O	[38]
<i>Curcuma longa</i>	Zingiberaceae	P	[39]
<i>Chenopodium ambrosioides</i>	Amaranthaceae	FE, O	[40]
<i>Cocos nucifera</i>	Arecaceae	O	[25]
<i>Convolvulus arvensis</i>	Convolvulaceae	LE	[41]
<i>Conyza dioscoridis</i>	Asteraceae	ZE	[41]
<i>Coriandrum sativum</i>	Apiaceae	SE, O	[42]
<i>Datura alba</i>	Solanaceae	LP	[43]
<i>Decalepis hamiltonii</i>	Asclepiadaceae	XP	[7]
<i>Eichhornia crassipes</i>	Pontederiaceae	LE	[44]
<i>Elaeis guineensis</i>	Arecaceae	O	[45]
<i>Elaeis guineensis</i>	Palmaceae	O	[46]
<i>Embelia ribes</i>	Myrsinaceae	FE, O	[47]
<i>Eucalyptus globules</i>	Myrtaceae	LP, M	[48]
<i>Foeniculum vulgare</i>	Apiaceae	FE	[49]
<i>Glycine max</i>	Fabaceae	O	[50]
<i>Jatropha gossypifolia</i>	Euphorbiaceae	SE	[51]
<i>Juniperus virginiana</i>	Cupressaceae	O	[52]
<i>Lantana camara</i>	Verbenaceae	TE	[45]
<i>Lonchocarpus</i> spp.	Leguminosae	O	[53]
<i>Lupinus albus</i>	Fabaceae	SE	[54]
<i>Lupinus termis</i>	Leguminosae	SE	[54]
<i>Melia azedarach</i>	Meliaceae	O, E	[55]
<i>Mentha citrate</i>	Lamiaceae	O	[56]
<i>Nicotiana tabacum</i>	Solanaceae	E	[57]
<i>Ocimum canum</i>	Lamiaceae	LP	[58]
<i>Ocimum kilimandscharicum</i>	Lamiaceae	O	[59]
<i>Piper nigrum</i>	Piperaceae	O, E	[60, 61]
<i>Polygonum hydropiper</i>	Polygonaceae	L	[62]
<i>Pongamia glabra</i>	Fabaceae	O, E	[61]
<i>Psidium guajava</i>	Myrtaceae	L, LP	[63]

TABLE 1: Continued.

Plant species	Family	Plant part	References
<i>Ryania speciosa</i>	Flacourtiaceae	YE	[64]
<i>Sapindus trifoliatus</i>	Sapindaceae	SP	[65]
<i>Schleichera trijuga</i>	Sapindaceae	O	[66]
<i>Sesamum orientale</i>	Pedaliaceae	O	[5]
<i>Sesamum indicum</i>	Pedaliaceae	O	[67]
<i>Syzygium aromaticum</i>	Myrtaceae	O	[68]
<i>Tagetes erecta</i>	—	X, Y	[69]
<i>Tanacetum cinerariaefolium</i>	Asteraceae	O, P	[55]
<i>Thujaopsis dolabrata</i>	Cupressaceae	E	[64]
<i>Trigonella foenumgraecum</i>	Fabaceae	SE	[70]
<i>Vitex negundo</i>	Lamiaceae	L	[71]

Note. L: leaves, B: bark, F: fruits, S: seeds, O: oil, P: powder, E: extract, M: vapour, R: Rhizome, T: plant, V: flower, X: root, and Y: stem, (Source: [5, 6]).

essential oils of plants *Xylopi aethiopic a*, *Vepris heterophylla*, and *Lupia rugosa* are used for protection of stored grains from attack of stored grain insect pests [114]. The components of citrus peels were used as grain protectant against *Callosobruchus maculatus* [133]. Coconut oil has been found effective against *Callosobruchus chinensis*, for a storage period of six months, when applied to *Vigna radiata* (green gram) at 1% [134]. Formulations of menthol were used as protection of pulse grain from attack of *Callosobruchus Chinensis* [135]. Spinosad, a naturally occurring insecticide from the actinomycete, *Saccharopolyspora spinosa*, has high efficacy, a broad insect pest spectrum, low mammalian toxicity, and minimal environmental profile is unique among existing products currently used for stored-grain protection [136].

4.5. Chemosterilants/Reproduction Inhibitors. Many researchers reported that plant parts, oil, extracts, and powder mixed with grain-reduced insect oviposition, egg hatchability, postembryonic development, and progeny production [137–139]. Lists of 43 plant species have been reported as reproduction inhibitors against stored product insects [32]. Reports have also indicated that plant derivatives including the essential oils caused mortality of insect eggs [82]. Many ground plant parts, extracts, oils, and vapour also suppress many insects [6, 7].

4.6. Insect Growth and Development Inhibitors. Plant extracts showed deleterious effect on the growth and development of insects and reduced larval pupal and adult weight significantly, lengthened the larval and pupal periods, and reduced pupal recovery and adult eclosion [140]. Rajasekaran and Kumaraswami [141] reported that grains coated with plant extracts completely inhibited the development of insect

TABLE 2: List of insecticidal active principles of plants.

Active principle	Plant species	Insect toxicity	Insect species	References
Anonaine	<i>Annona reticulata</i>	Contact	<i>Callosobruchus chinensis</i>	[72]
Azadirachtin	<i>Azadirachta indica</i>	Contact; IGR	Stored grain pests, aphids	[30]
E-Anethole	<i>Foeniculum vulgare</i>	Contact	<i>Sitophilus oryzae</i> , <i>Callosobruchus chinensis</i>	[49]
β -Asarone	<i>Acorus calamus</i>	Contact;	Stored grain pests	[73]
Z-Asarone	<i>Acorus calamus</i> ; <i>Acorus gramineus</i>	Contact	<i>Sitophilus zeamais</i>	[26]
Bornyl acetate	<i>Chamaecyparis obtuse</i>	Contact	<i>Sitophilus oryzae</i>	[27]
Camphor	<i>Ocimum kilimandscharicum</i>	Contact	<i>Sitophilus oryzae</i>	[59]
(+)-3-Carene	<i>Baccharis salicifolia</i>	Contact	<i>Tribolium castaneum</i>	[59]
Carvacrol	<i>Thujopsis dolabrata</i>	Contact; fumigant	<i>Sitophilus oryzae</i> , <i>Callosobruchus chinensis</i>	[60]
Carvone	<i>Carum carvi</i>	Contact	<i>Sitophilus oryzae</i> , <i>Rhyzopertha dominica</i>	[74]
1,8 Cineole	<i>Eucalyptus</i>	Contact; fumigant	<i>Rhyzopertha dominica</i> <i>Tribolium castaneum</i>	[38]
Cinnamaldehyde	<i>Cinnamomum aromaticum</i>	Contact	<i>Tribolium castaneum</i> , <i>Sitophilus zeamais</i>	[37]
Dioctyl hexanedioate	<i>Conyza dioscoridis</i>	Contact	<i>Tribolium castaneum</i> , <i>Sitophilus granaries</i>	[41]
Eugenol	<i>Citrus</i>	Fumigant	<i>Sitophilus oryzae</i>	[38]
Estragole	<i>Foeniculum vulgare</i>	Contact	<i>Sitophilus oryzae</i> <i>Lasioderma serricornne</i>	[31]
(+)-Fenchone	<i>Foeniculum vulgare</i>	Contact	<i>Sitophilus oryzae</i> <i>Lasioderma serricornne</i>	[31]
Hexa decane	<i>Chenopodiumambrosioides</i>	Contact	<i>Tribolium castaneum</i> , <i>Sitophilus granaries</i>	[41]
Hexadecanoic acid	<i>Convolvulus arvensis</i>	Contact	<i>Sitophilus oryzae</i> , <i>Rhyzopertha dominica</i> .	[41]
Linalool	<i>Ocimum canum</i> Sims	Fumigant	<i>Tribolium castaneum</i> , <i>Sitophilus granaries</i>	[75]
Limonene	<i>Citrus</i>	Contact	<i>Tribolium castaneum</i>	[27]
(-)-Limonene	<i>Baccharis salicifolia</i>	Contact; fumigant	<i>Tribolium castaneum</i>	[31]
Nicotine	<i>Nicotiana tabacum</i>	Contact	Mites, aphids, thrips, leafhopper	[39]
Pyrethrin I and II	<i>Tanacetum cinerariaefolium</i>	Contact; stomach poison	Stored grain pests, crop pests	[76]
β -Pinene	<i>Baccharis salicifolia</i>	Contact	<i>Tribolium castaneum</i> ,	[27]
α -Pinene	<i>Baccharis salicifolia</i>	Fumigant	<i>Tribolium castaneum</i> ,	[27]
Rotenone	<i>Lonchocarpus</i> sp.	Contact; stomach poison	Crop pests, lace bugs, <i>Sitophilus oryzae</i>	[55]
Ryania	<i>Ryania speciosa</i>	Contact; stomach poison	Potato beetle, aphids, lace bugs, stored grain pests	[77]
Sabadilla	<i>Schoenocaulon officinale</i>	Contact; stomach poison	Stinks, thrips, squash bugs, leaf hoppers, caterpillars	[78]
Spinosyn A and D	<i>Saccharopolyspora spinosa</i>	Stomach poison	Stored grain pests	[79]

like *Sitophilus oryzae*. Plant derivatives also reduce the survival rates of larvae and pupae and adult emergence [101]. Development of eggs and immature stages inside grain kernel were also inhibited by plant derivatives [102]. The crude extract also retarded development and caused mortality of larvae, cuticle melanisation, and high mortality in adults [142].

5. Some Important Phytochemicals with Insecticidal Properties

The botanical insecticides that have primarily been used and are commercially available include ryania, rotenone, pyrethrin, nicotine, azadirachtin, and sabadilla (Tables 2 and 3).

TABLE 3: Insecticidal activity and mammalian toxicity of some natural insecticides.

Natural insecticides	Insect toxicity*	Mammalian toxicity Oral (rat) LD ₅₀ (mg/kg b.w.)
Anethole	C, S	2090
β -asarone	C, S	275
Azadirachtin	IGR, R	13000
Carvacrol	C	810
1,8-Cineole	C, F	2480
Cinnamaldehyde	C	1160
Cuminic aldehyde	C, S	1390
Eugenol	C, F	500
Nicotine	C	50
Pyrethrin I and II	C, S	1200
Rotenone	S	350
Ryania	C, S	750
Sabadilla	C, S	5000
Spinosad	C	3738

*C: contact, S: stomach poison, F: fumigant, IGR: insect growth regulator, and R: repellent [80–82].

5.1. *Ryania*. The active components of ryania are derived from the roots and woody stems of the plant *Ryania speciosa*, native to Trinidad [143]. *Ryania* has low mammalian toxicity, with a median lethal dose (LD₅₀) of 750 mg/kg and works as both contact and stomach poison. It has long residual activity among the botanical insecticides. This botanical insecticide has a unique mode of action and affects muscles by binding to the calcium channels in the sarcoplasmic reticulum. This causes calcium ion flow into the cells, and death follows very rapidly [20]. *Ryania* works best on caterpillars (i.e., codling moth, corn earworm); however, is it also active on a wide range of insects and mites, including potato beetle, lace bugs, aphids and squash bug [144].

5.2. *Rotenone*. Rotenone is derived from the roots of the two plants: *Lonchocarpus* sp. and *Derris* sp. are both legumes originally from the East Indies, Malaya and South America. Rotenone is a moderately of the toxic botanical insecticides, with an LD₅₀ of 132 mg/kg to mammals [81]. In fact, rotenone is more toxic to mammals than both carbaryl and malathion, two commonly used synthetically derived insecticides. Also, rotenone is extremely toxic to fish [55]. This botanical insecticide works as both contact and stomach poison. Rotenone is slower acting than most other botanical insecticides, taking several days to kill pests; however, pests stop feeding almost immediately. It degrades rapidly in air and sunlight. Rotenone blocks respiration by electron transport on the complex I. Rotenone shows broad spectrum of activity on many insects and mite pests, including leaf-feeding beetles, caterpillars, lice, mosquitoes, ticks, fleas, and fire ants [145].

5.3. *Pyrethrin/Pyrethrum*. Pyrethrin I and II are derived from the seeds or flower of *Chrysanthemum cinerariaefolium* [55, 146] which is grown in Africa, Ecuador, and Kenya. Pyrethrin has a low mammalian toxicity. However, cats are highly susceptible to pyrethrin poisoning. The LD₅₀ of pyrethrin is 1200 to 1,500 mg/kg [81, 147, 148]. Pyrethrin is one of the oldest household insecticides still available and is fast acting, providing almost immediate “knockdown” of insects following an application. It works as both a contact and a stomach poison. The material has a very short residual activity-degrading rapidly under sunlight, air and moisture, which means that frequent applications may be required. Pyrethrin can be used up until harvest, as there is no waiting interval required between initial application and harvest of food crops [149].

The way pyrethrin kills insects (mode of activity) is by disrupting the sodium and potassium ion-exchange process in insect nerves and interrupting the normal transmission of nerve impulses. Pyrethrin has activity on wide range of insects and mites, including flies, fleas, beetles, and spider mites [150].

5.4. *Nicotine*. Nicotine, which is derived from *Nicotiana tabacum*, is toxic to mammals among the botanical insecticides with an LD₅₀ between 50 and 60 mg/kg [55, 151]. It is extremely harmful to humans. Nicotine, a fast-acting nerve toxin, works as a contact poison. It kills insects (and humans) through bonding to receptors at the nerve synapses (junctures), causing uncontrolled nerve firing, and by mimicking acetylcholine (Ach) at the nerve-muscle junctions in the central nervous system [152].

Certain plant types, such as roses, may be harmed or injured by nicotine sprays. Nicotine is most effective on soft-bodied insects and mites, including aphids, thrips, leafhoppers, and spider mites. Many caterpillars are resistant to nicotine [153].

5.5. *Azadirachtin*. Azadirachtin is derived from the tree *Azadirachta indica*, grown in India and Africa [55]. Azadirachtin has an extremely low mammalian toxicity and is least toxic of the commercial botanical insecticides, with an LD₅₀ of 13,000 mg/kg. Azadirachtin is considered a contact poison; however, it has “some” systemic activity in plants when applied to the foliage. The material is generally nontoxic to beneficial insects and mites. Azadirachtin has broad mode of activity, working as a feeding deterrent, insect-growth regulator, repellent, and sterilant; and it may also inhibit oviposition [55, 154]. The material is active on a broad range of insects, including stored grain pests, aphids, caterpillars and mealybugs [30].

5.6. *Sabadilla*. Sabadilla is derived from the seeds of plant *Schoenocaulon officinale*, which is grown in Venezuela. Sabadilla is one of the least toxic registered botanical insecticides, with mammalian LD₅₀ of 5,000 mg/kg. Sabadilla works as contact toxicant and a stomach poison. Similar to other botanical insecticides, the material has minimal residual activity and degrades rapidly in sunlight and moisture

(rainfall). *Sabadilla* works by affecting nerve cell membranes, causing loss of nerve function, paralysis, and death [146]. It is effective against caterpillars, leaf hoppers, thrips, stink, and squash bugs.

5.7. Avermectins. Avermectins, which are macrocyclic lactones, are derived from the actinomycete, *Streptomyces avermitilis* [155], lethal dosage of 50% in range of 10–11.3 mg/kg for rat. This molecule is most effective against agricultural pests with lethal concentration of 90% (LC₉₀) in the range of 0.02 ppm for mites and has somewhat least toxicity to stored products pests. It is effective on internal parasites of domestic animals [156]. Avermectins block the neurotransmitter GABA at the neuromuscular junction in insects and mites. Visible activity, such as feeding and egg laying, stops shortly after exposure, though death may not occur for several days [157].

5.8. Spinosads. Spinosad is a mixture of spinosyn A and spinosyn D and was originally isolated from the soil Actinomycete, *Saccharopolyspora spinosa* [158]. Spinosad is recommended for the control of a very wide range of caterpillars, leaf miners and foliage-feeding beetles. Spinosyns have a novel mode of action, primarily targeting binding sites on nicotinic acetylcholine receptors that are distinct from those at which other insecticides exert activity, leading to disruption of acetylcholine neurotransmission [79, 159].

5.9. (Z) Asarone. (Z) Asarone is natural insecticide isolated from *Acorus calamus* L. [26]. This molecule is more effective against adults of *Sitophilus oryzae*, *Lasioderma serricorne*, and *Callosobruchus chinensis* and shows both fumigant and contact toxicity. Some studies show that the molecules possess *in vivo* carcinogenic effects [160] and *in vitro* mutagenic activities [161]. Further, this molecule induces structural chromosome aberration in human lymphocytes *in vitro* [162]. Due to its mammalian toxicity [81, 163], the molecule is unsafe for grain treatment.

6. Challenges to the Utilization of Botanicals Pesticides

Many plant species contain secondary metabolites that are potent against several pest species. Not only are some of the plants (e.g., the neem trees) of major interest as sources of phytochemicals for more environmentally benign grain/crop protection. Phytochemical products can increase income of rural farmers and promote safety and quality of food and life in general [8, 164].

The successful utilization of botanicals can help to control many of the world's destructive pests and diseases, as well as reduce erosion, desertification, deforestation, and perhaps even reducing human population by acting as spermicide (although this will be considered a major negative effect by many cultures and religions) [165]. Although the possibilities of using botanical pesticides seem almost endless, many details remain to be clarified. Many obstacles must be overcome and many uncertainties clarified before

their potential can be fully realized. These limitations seem surmountable; however, they present exciting challenges to the scientific and economic development communities. Solving the following obstacles and uncertainties may well bring a major new resource which will benefit much of the world. These obstacles include:

- (i) lack of experience and appreciation of the efficacy of botanicals for pest control. There are still doubts as to the effectiveness of plant-derived products (both "home-made" and commercial products) due to their slow action and lack of rapid knockdown effect;
- (ii) genetic variability of plant species in different localities;
- (iii) difficulty of registration and patenting of natural products and lack of standardization of botanical pesticide products;
- (iv) economic uncertainties occasioned by seasonal supply of seeds, perennial nature of most botanical trees, and change in potency with location and time with respect to geographical limitations;
- (v) handling difficulties as there is no method for mechanizing the process of collecting, storing, or handling the seeds or leaves or flowers from some of the perennial trees;
- (vi) instability of the active ingredients when exposed to direct sunlight;
- (vii) competition with synthetic pesticides through aggressive advertising by commercial pesticides dealers and commercial-formulated botanicals are more expensive than synthetic insecticides and are not as widely available;
- (viii) rapid degradation, although desirable in some respects, creates the need for more precise timing or more frequent applications;
- (ix) Data on the effectiveness and long-term (chronic) mammalian toxicity are unavailable for some botanicals, and tolerances for some have not been established.

7. Conclusion

Many authors have evaluated the insecticidal (grain protectant) properties of plant products on various species of stored product insect pests. The results clearly show that it is possible to develop methods for grain protectants with reduced use of synthetic chemical insecticides. The main advantages of botanical pesticides are ecofriendly, easily biodegradable, nontoxic to nontarget organisms, and many plant-derived natural products acting against insects could be produced from locally available raw materials. They have been numerous botanical pesticides studied at the laboratory level. Research efforts should focus not only on their efficacy, but also on mammalian toxicity, mode of action in insects, seed germination, effect on nutritional quality, seedling growth, and stability of the compound. The insecticides of

plant origin could be exploited for the development of novel molecules with highly precise targets for sustainable insect pest management in stored grain.

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