Current Status and Future Prospects of Contact Insecticides in Stored-Product Protection

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Abstract

Historically, contact insecticides have played a major role in managing pests in postharvest stored commodities. Despite the availability of significant literature published over the past three decades, the current status and potential future use of contact insecticides are not known. In this review we synthesize the literature to identify reasons for the ongoing decline in the use of contact insecticides in postharvest commodity protection, and outline the challenges and opportunities for their future use by the grain industry. Development of resistance in major stored-product insect pests to conventional pesticides and the stricter regulatory requirements driven by consumer sensitivity to pesticide residues on food are discussed in detail to explain the limitations to their current use. We also highlight the strategic integration of currently available contact insecticides into a fumigation-dominated pest management program. We conclude by proposing several research aspects that may prompt their continued use by the grain industry in the near future.

INTRODUCTION

Contact insecticides play a critical role in protecting cereal grains, flour, oil seeds, pulses, dried fruits, and packaged and processed foods from various insect pests during storage. Some of these insecticides are applied directly onto the commodities at the time of storage (protectants), and others are applied to the storage structures (structural treatments) or dispensed into the storage space (aerosols). For decades there has been a gradual decline in their use due to increasing regulatory restrictions, consumer sensitivity to chemical residues, development of resistance in major pest species, and high costs involved in the development and registration of new chemistries (7). International import and export regulations addressing food biosecurity could be even more stringent in the coming years. However, contact insecticides are still major components of integrated pest management (IPM) programs across the food storage sector. Despite the continued use of insecticides for the management of insect pests of stored food commodities over several decades, there has not been a comprehensive review of their status in pest management programs since 1996 (7). A significant amount of research exists on the development of novel active ingredients (e.g., biopesticides such as spinosad and flavesone) and reduced-risk insect growth regulators (e.g., S-methoprene). In addition, the phasing out of the fumigant methyl bromide has led to the over-reliance on the alternative fumigant phosphine, which has resulted in resistance development in major storage pest species. Restrictions on the usage and application of phosphine, as well as the withdrawal of many traditional active ingredients, have triggered renewed interest in contact insecticides. In this review, we synthesize the available literature to identify gaps in our knowledge of the use of contact insecticides in the storage sector and to communicate recent advances and future trends to researchers and practitioners actively involved in the management of stored-product pests (SPPs).

IMPORTANCE OF INSECT PESTS IN STORED FOOD COMMODITIES

Physical Damage to Durable Raw and Processed Commodities by SPPs

Of the 32 taxonomic orders of insects, species belonging only to Coleoptera (beetles), Lepidoptera (moths), and Psocoptera (psocids) have been identified as SPPs that reportedly inflict damage to all types of stored commodities, including grains, pulses, dried fruits, seeds, and plant and animal materials (96, 149). The earliest review of the assessment and reduction of grain weight loss due to SPPs was undertaken by Parkin (139). However, targeted research exclusively assessing the real damage potential of SPPs without the interference of other factors was first reported by Rao & Wilbur (148). Their study demonstrated a cumulative weight loss of wheat of up to 56.9% as a direct result of feeding by developing stages and adults of the lesser grain borer, *Rhyzopertha dominica* (F.), over a period of 2 months. **Table 1** summarizes published data on assessments of damage to grain caused by six major species of SPPs using two well-established methods: (*a*) measurement of weight loss and (*b*) quantification of the proportion of damaged grains in a sample. The highest level of potential percentage weight loss of wheat (94%) by the major quarantine pest khapra beetle, *Trogoderma granarium* Everts (100), and close to 100% damage (99.4%) of barley by the Angoumois grain moth, *Sitotroga cerealella* (Olivier) (43), justifies the application of control strategies that include contact insecticides to manage SPP infestations and reduce physical damage of stored commodities (**Table 1**).

Qualitative Damage by SPPs and the Impact on Public Health

Apart from causing physical damage to stored commodities, infestations from SPPs can lead to serious quality degradations that may render a commodity unsuitable for consumption and

Table 1   Maximum potential damage of stored products reported in global experimental studies undertaken involving major stored-products pests

Pest species	Percentage weight loss[a]	Percentage damage[b,c]
Primary pests		
Callosobruchus maculatus (F.)	60% (Cowpeas) (174)	97.8% (Cowpeas) (99)
Lasioderma serricorne (F.)	60% (Fennel seeds) (51)	67% (Fennel seeds) (151)
Rhyzopertha dominica (F.)	83% (Wheat) (31)	81% (Wheat) (93)
Sitotroga cerealella (Olivier)	50% (Barley) (43)	99.4% (Barley) (43)
Sitophilus oryzae (L.)	38% (Maize) (111)	95% (Sorghum) (183)
Trogoderma granarium Everts	94% (Wheat) (100)	31% (Wheat) (157)
Secondary pests		
Cryptolestes ferrugineus (Stephens)	12% (Cracked maize) (48)	ND
Oryzaephilus surinamensis (L.)	14% (Corn flour) (90)	ND
Plodia interpunctella (Hübner)	33% (Almonds) (72)	ND
Tribolium castaneum (Herbst)	28% (Chickpeas) (104)	73% (Wheat) (29)

[a]Percentage weight loss $= \left(\frac{\text{initial grain weight} - \text{final grain weight}}{\text{initial grain weight}} \right) \times 100$.

[b]Percentage damage $= \left(\frac{\text{number of damaged grains}}{\text{total number of grains in sample}} \right) \times 100$.

[c]Percentage of damaged grains cannot be determined in most secondary pests because of their requirement for already damaged or milled grain.

Abbreviation: ND, not determined.

significantly reduce its market value through lower grading (78, 98, 130). Qualitative degradation due to SPP infestations includes the presence of insect fragments in grains, flour, and processed food (46, 176); reduced germination in seeds and biochemical deterioration (102); increased temperature and moisture content of grains and synergistic development of fungi, leading to discoloration, off-odor, and the production of mycotoxins (92, 98, 172); and the induction of resistance to antibiotics through the spread of enterococci (140).

Reviews and book chapters have also synthesized published information on the impact of SPPs on human health (6, 98, 116, 127, 130). SPPs can inflict allergic reactions in personnel handling infested grain and processed materials (98, 127, 130). The World Health Organization and International Union of Immunological Societies (WHO/IUIS) Allergen Nomenclature Subcommittee has included two SPPs in its allergens list: the booklouse *Liposcelis bostrychophila* Badonnel and the Indian meal moth, *Plodia interpunctella* (Hübner) (98). Moreover, the red flour beetle, *Tribolium castaneum* (Herbst), and the confused flour beetle, *T. confusum* Jacquelin du Val, can pose serious health hazards by secreting benzoquinones that have carcinogenic properties (116). In situations of severe infestation, swarms of psocids have made walkways and storage handling machinery slippery for the grain handlers, thereby exposing them to injury (146).

Estimates of Economic Consequences if Stored Food Commodities Are Not Protected

As shown in **Table 1**, the economic impact due to physical damage from SPP infestations can be extensive if harvested durable commodities are not protected during storage. One of the earliest monitoring programs undertaken in the United States for over a decade (1951–1960) reported annual losses of 325 million bushels of whole grain commodities as a direct result of infestations from major SPPs, even in the presence of chemical treatments (179). The value of this lost commodity was estimated at $454.8 million, with a further reported loss of $8.8 million incurred due

Mycotoxin: naturally occurring toxin produced by certain molds (fungi) that is found in food commodities

to SPP infestations in processed cereal products (179). For the Indian subcontinent alone, losses attributed to SPP problems were estimated at approximately $364 million (40), while estimations of annual commodity losses of up to $4 billion were reported for sub-Saharan Africa (192), and approximately 10–20% of loss of total production had been estimated for developing countries (122).

Apart from the potential economic loss resulting from physical damage caused by SPPs, their mere presence in commodities can lead to the rejection of consignments, and the loss of markets may have far-reaching economic implications. For example, to meet consumer expectations for insect-free clean and safe grain commodities and to attract premium price, the grain industry in Australia has self-imposed a nil tolerance policy for live insects in its exported grain (84). Failure to meet the phytosanitary requirements of importing countries can cause serious economic losses, as highlighted by a case where Egypt rejected an $84 million shipload of US soft red wheat due to the detection of live insects (77). Containment and eradication of the notorious quarantine pest *T. granarium* in the United States reportedly cost $8.4 million in the 1950s (106). Lupo (121) highlighted the significant economic losses incurred by commercial food companies due to product recall as a direct result of the presence of SPPs, leading to consumer complaints and litigation, audit failure, brand damage, and loss of product.

Aeration: process of moving small volumes of air through stored grain to cool or ventilate it to maintain its moisture content

USE OF CONTACT INSECTICIDES IN STORED-PRODUCT PEST MANAGEMENT

Role of Contact Insecticides in Integrated Pest Management

An IPM program for SPPs may involve judicious utilization of available control methods, including sample screening and inspections for SPPs, trapping, hygiene, drying and cooling, heat treatment, controlled atmosphere, and chemical treatments (65). Among these, chemical treatments such as the use of fumigants and contact insecticides are at the frontline due to their measurable and quick impact. While contact insecticides are used to protect commodities from insect attack, fumigants are used to disinfest the commodities when infestations are detected. Although highly successful, fumigants are not suitable for application in structures that are not airtight; furthermore, they do not provide long-term protection, and reinfestation after fumigation is possible (65). Currently, resistance to the key fumigant phosphine in SPPs is a worldwide problem (132), which justifies the expanded use of protectants (3). Aeration, although effective, may also have limited applicability in tropical areas where temperatures are not cool enough to effectively utilize aeration (115). A great example of industry adoption of an integrated pest and resistance management (IPRM) decision-making model in a stored commodity where currently registered contact insecticides are being used strategically within a phosphine-dominant pest management system has been well-demonstrated in Australia (132, 133, 134).

The history of using contact insecticides to treat grain and storage structures to protect commodities from various SPPs goes back many decades (7). These treatments are being used specifically for freshly harvested grain stored on-farm and in bulk storage facilities, with the most used active ingredients belonging to organophosphorus compounds (e.g., malathion, chlorpyrifos-methyl, fenitrothion), pyrethroids (e.g., permethrin, deltamethrin), carbamates (e.g., carbaryl), and insect growth regulators (e.g., hydroprene, methoprene) (7). Nevertheless, the withdrawal of several contact insecticides due to regulatory restrictions, the widespread development of resistance, and the difficulty of developing and registering new compounds make the preservation of existing contact insecticides a high priority.

Grain protectants are generally defined as contact insecticides that are applied to raw grains as they are loaded into storage structures and theoretically leave residues to protect the grain from

IS THERE A ROLE FOR FIELD CROP PESTICIDES IN POSTHARVEST COMMODITY PROTECTION?

Active ingredients of contact insecticides registered for managing pests of field and orchard crops are not usually intended for use in postharvest commodity protection. Many insect pests of field crops and postharvest commodities belong to the same orders, such as Coleoptera (beetles) and Lepidoptera (moths). Moreover, several crop protection insecticides used against field crop pests and stored commodities belong to the same groups of insecticides, such as organophosphates and pyrethroids. Despite these overlapping aspects, major hindrances to extending the registration of contact insecticides to postharvest use have been investment limitations, driven by a market segment narrower than that for field crop protection, and risks associated with stricter regulatory requirements, such as maximum residue levels on food materials. Therefore, while there has historically been an array of options available for crop protection in the field, the storage sector juggles with only a few active ingredients. It is highly unlikely that there would be new discoveries of chemistries in the near future. In this scenario, a major research gap to be explored is whether some of the existing active ingredients used in the preharvest sector can be utilized in the storage sector, the final and most critical stage of the agro-food supply chain.

insect invasion and damage during the storage period, whereas structural treatments are applied to empty storage structures and machinery as part of sanitation or hygiene (7). These are best considered preventative treatments and are used across several types of storage, including elevator silos, farm storage bins, flat storage structures, and storage bags (35). Because these treatments are preventative, there is considerable discussion about whether they are valid components of traditional IPM programs.

Protectant (Admixture) Treatments for Long-Term Storage of Bulk Raw Commodities

The availability of protectants in today's world varies broadly among most developed countries. Regulatory actions and market considerations could eliminate some grain protectants that are currently used, though these regulations differ widely by country and region. Older organophosphate and carbamate insecticides are being withdrawn with only a few instances of replacement with new reduced-risk insecticides (12, 161). A more likely scenario is that an insecticide already registered for field, raw, and orchard crops will be expanded for use on stored grains (see the sidebar titled Is There a Role for Field Crop Pesticides in Postharvest Commodity Protection?). For example, in the United States, the insect growth regulator methoprene is available for use in stored products as a stand-alone formulation or in combination with the pyrethroid deltamethrin with or without the synergist piperonyl butoxide (14). Research on the use of methoprene on stored grains includes long-term residual efficacy studies of various commodities (13, 57), different application methods such as layer treatments to a grain mass (25), sublethal effects such as movement after exposure to methoprene formulations (124), and decreases in progeny production after exposure (19, 66). Another example is the bacterium-derived insecticide spinosad, which is effective against various SPPs (62, 95) and is now registered in several countries (95).

Residual Structural Treatments

In their broader sense, residual surface treatments correspond to a spectrum of application scenarios, from surfaces of empty silos to storage bags and packages. Insecticides currently used as fabric, structure, or crack and crevice treatments, based on their registration, fall under three broad

categories, which can vary from country to country. The first category includes insecticides registered as both grain protectants and structural treatments. Two examples are the organophosphorus compound pirimiphos-methyl and the pyrethroid deltamethrin, which have been extensively used in many countries (7). The second category consists of insecticides registered solely for structural treatments for sanitation and hygiene of storage structures. Examples include active ingredients such as the pyrethroid cyfluthrin and the nonneurotoxic compound chlorfenapyr, which are currently not allowed to be applied directly to the commodity but their use has been extended to storage structures (154, 169). Finally, insecticides of the third category are registered exclusively as grain protectants and not for structural treatment. Spinosad is one such example, despite its proven effectiveness against SPPs on treated structures (95).

The type of surface to be treated is a critical parameter that determines the efficacy of a certain contact insecticide. In general, many of the insecticides that have been tested so far seem to be less effective on concrete surfaces than on other types of surfaces; this is because concrete surfaces are porous and alkaline, two characteristics that are detrimental to many insecticides (4, 8, 125, 126, 152, 181). For instance, Agrafioti et al. (4) tested several active ingredients on concrete and metal surfaces for the control of adults of the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.), and *T. confusum* and found that most of these insecticides were more effective on metal surfaces. Nevertheless, some insecticides are equally effective on different surfaces (8, 10, 11, 18). In fact, Arthur (10) found that the pyrrole chlorfenapyr was more effective on concrete surfaces than on tile or plywood for the control of *T. castaneum* and *T. confusum* adults. Although the above-cited studies demonstrated the variations in bioefficacy of insecticide treatments on different substrate surfaces, further research is needed to specifically reveal the influence of these surfaces on the chemical activities of currently registered insecticides.

One of the most interesting cases that has received increased attention during the last decade is the use of insecticide-impregnated or insecticide-coated nets (82, 189, 190). Among the first formulations tested for this purpose was a net coated with the pyrethroid alpha-cypermethrin, which tested successfully initially against pests of stored tobacco, such as the cigarette beetle, *Lasioderma serricorne* (F.), and the tobacco moth, *Ephestia elutella* (Hübner) (27, 154), and later against many other SPPs (2, 81, 82). Storage bags impregnated with insecticides provide a considerable residual effect for long periods, and even short exposures of insects to the treated substrate may result in an increased delayed mortality (82, 141, 189). Impregnated bags can be combined with hermetic bags in one single bag type, which provides an immediate effect on SPPs as well as long-term protection via a reduced oxygen environment (158).

Aerosols for Space Treatments in Food Processing Facilities and Warehouses

Aerosols used to treat the interior of structural facilities to control SPPs are liquid insecticides atomized or misted through delivery systems as contact insecticides (11). They are intended to spread and disperse throughout the facility, but unlike fumigants, they have little or no penetrating action. Studies of adulticides and insect growth regulators such as methoprene applied as aerosols show that particle sizes of 16 μm are more effective at dispersing and adhering to either the insect body surface or a flooring surface than smaller particle sizes of 2 μm (20, 23, 113). Smaller particle sizes may dissipate before either coming into contact with an exposed insect or adhering to a flooring surface (16, 17, 23). If particles are too small, they may hang in the air and not be deposited onto a flooring surface inside a facility, or if particle sizes are too large, then dispersal can also be affected (42). During aerosol spray operations, the particles may not be equally distributed in the target area, leading to unequal dispersion and the creation of untreated areas that provide refugia and escape from exposure (15, 16, 17, 159).

Hermetic bag: completely airtight bag, which creates a reduced-oxygen environment and is used for storing grain, making it unsuitable for insect survival

The structural complexity of processing facilities, such as flour mills, may block aerosol particles from reaching their target, especially in zones that are more distant from the location of the sprayer (15, 16, 159). For instance, Scheff et al. (159) noted that zones close to walls, corners, and equipment, especially when they are away from the application location, may receive less insecticide, which in turn results in reduced mortality patterns of the insects that are exposed at these areas. Moreover, the presence of food sources is expected to increase survival due to insect feeding but also because insects within food refugia can escape contact with the insecticide (11, 16). This finding clearly suggests the importance of sanitation before the application of aerosols. Finally, dissipation of many contact insecticides is more rapid when exposed to light; thus, applications in illuminated areas may not be equally effective as those that are carried out in dark areas (152, 169, 180).

WELL-RESEARCHED CONTACT INSECTICIDES YET TO OR UNLIKELY TO RECEIVE INDUSTRY ADOPTION

Diatomaceous Earth and Related Inert Materials

Diatomaceous earth (DE), i.e., the fossils of diatoms, is among the most thoroughly investigated nonconventional treatment for the management of SPPs in postharvest grain and storage structures, with hundreds of research reports published within the past 25 years since the review by Korunić (110). DE has a mechanical mode of action on insects, as it inactivates the epicuticular lipids, causing death through desiccation, although abrasion has been postulated as a secondary mode of action (110, 193). The application rates of DE are considerably higher than those of traditional grain protectants/structural treatments and may exceed 1,000 ppm (i.e., 1 g per kilogram of grain) (110, 173). DE generally is more effective at elevated temperatures, at which SPPs have greater metabolism and activity, and at reduced relative humidity/moisture content levels, at which insects experience increased water stress (26, 37, 110, 173). For example, in a laboratory study of *Sitophilus zeamais*, the insecticidal efficacy of dust ashes from three tree plant species combined with a DE formulation (SilicoSec) was tested at three temperatures (15°C, 20°C, and 25°C) and two relative humidity levels (55% and 75%). Significantly higher mortality was observed in most treatments at elevated temperatures in combination with lower relative humidity (37).

In pursuit of natural products as alternatives to synthetic insecticides, several inert materials with a similar mode of action and at comparable application rates to those of DE, including zeolites, volcanic ash and wood ash, kaolin, and attapulgite, have also been extensively evaluated against various SPPs (37, 44, 73, 137, 153). Graphene, a nanomaterial that consists of a single layer of atoms, has shown good potential for controlling SPPs at concentrations that were lower than those applied for other inert materials (112). Although these inert materials are alleged to be food grade and their presence on grain is considered safe for human consumption, this claim has never been substantiated through published reports and is an area in need of further research.

Although these naturally occurring materials are being promoted as environmentally friendly, several shortcomings hinder their registration for broad adoption by industry and restrict their use to hygiene and sanitation treatments only. These include their ability to reduce the bulk density of the grains, causing respiratory problems, including silicosis and chronic bronchitis in workers who inhale these dusts; interference with the efficiency of machinery handling treated grain; and difficulties in application to bulk grain (110, 173).

Botanical Insecticides

Another group of materials that have been evaluated extensively for stored-product protection in parallel with synthetic insecticides is plant-derived botanical substances. Due to the enormity of

Nanomaterial: a material consisting of particles in nanoscale dimension (one millionth of a millimeter) or one that is produced by nanotechnology

Silicosis: a long-term lung disease caused by inhalation of silica dust (a mineral found in soil, sand, and natural rock)

the research undertaken in the area, comprehensive reviews and book chapters have been published regularly since the 1990s (28, 162, 164, 166, 171, 187). Plant products have been widely evaluated in the laboratories across the globe, but only a few products could pass the registration process for their application in the storage sector. Plant-derived botanical substances used against SPPs are chemically diverse mixtures (phytocomplexes) (123) that can affect arthropod nervous systems, reproduction, or behaviors. Extensive laboratory trials have been dedicated to formulating phytocomplexes that were applied as liquids (sprays, aerosols, grain admixtures) or solids (leaves, powders, dusts, ash) (83, 171) or incorporated into packaging (163, 182). Information on their effectiveness so far indicates that the highest level of susceptibility toward SPPs belongs to Coleoptera, followed by Lepidoptera and Psocoptera (45, 117). Unfortunately, apart from the successful commercial registration of neem and pyrethrum (28, 188), the future of plant extracts for stored-product protection, especially for use as grain protectants, remains uncertain and would require additional research data other than their preliminary insecticidal value (28). A challenge with most botanicals is that small-scale validation studies are limited mostly to developing countries and that global industrial validation is largely lacking. Other issues hinder the wider acceptance of botanical substances, including the absence of complete toxicological and environmental data (123), inconsistent efficacy reporting, undesirable odors, chemical variability of mixtures, low stability, susceptibility to degradation (45, 187), and relatively high costs related to the large quantities needed for their effective use (187).

RESISTANCE DEVELOPMENT IN KEY PEST SPECIES AND ITS MANAGEMENT

Resistance to Major Groups of Contact Insecticides and Cross-Resistance

As for other insect groups, the development of resistance to contact insecticides in SPPs is an evolutionary phenomenon where repeated exposures of a population to a treatment act on genotypic variation to select for increased tolerance in individuals in that population. Global research over the last three decades on various aspects of resistance development in major SPP species to several contact insecticides has been synthesized and well-documented through reviews and book chapters (41, 56, 65, 136, 147, 165). The development and spread of resistance to contact insecticides are influenced by several biological and ecological factors, including the mode of inheritance, the fitness costs associated with individual pests carrying resistance genes, and the spatiotemporal movement of resistant populations. The widespread failure of malathion to control SPPs in the 1960s led to a global survey that revealed the prevalence of resistance to this compound in several countries (50). Over the following two decades industry has witnessed the discovery and registration of several alternative treatments belonging to organophosphates, pyrethroids, and insect growth regulators, but the development of resistance to these treatments across a broad spectrum of SPPs seriously limited their effective use. Arthur (7) reviewed the resistance trend until the mid-1990s, and since then, there have been numerous cases of resistance in key pest species, including *R. dominica*; *T. castaneum*; the rice weevil, *Sitophilus oryzae* (L.); and the maize weevil, *S. zeamais* (Motschulsky), with maximum resistance incidences reported from Australia, Brazil, and the United States (**Table 2**). The discovery and registration of spinosad in the mid-2000s have been successfully used by industry to manage *R. dominica* populations with multiple resistances, but its effectiveness against several other SPPs has been limited (58, 95, 131). Although laboratory selection experiments suggested potential resistance development to spinosad in *R. dominica* (185), comprehensive resistance monitoring in Australia revealed no such resistance incidents in the field (129, 133).

Table 2   Resistance detections across the globe in key stored-product pests to major contact insecticides

Contact insecticides	Insect species	Country of resistance detection	Reference(s)
Insect growth regulators			
Hydroprene	*Plodia interpunctella*	United States	97
Methoprene	*Cryptolestes ferrugineus, Oryzaephilus surinamensis, Rhyzopertha dominica, Sitophilus oryzae, Tribolium castaneum*	Australia	58, 60
Organochlorines			
DDT	*Sitophilus zeamais*	Brazil	86, 150
Lindane	*Sitophilus zeamais*	Mexico	143
Organophosphates			
Chlorpyrifos-methyl	*Cadra cautella*	Australia	59
	Cryptolestes ferrugineus	Australia	58
	Oryzaephilus surinamensis	Australia	58
		Wales	34
	Rhyzopertha dominica	Australia	58, 59
		Brazil	85
	Sitophilus granarius	Serbia	107, 108
	Sitophilus oryzae	Australia	58, 59
	Sitophilus zeamais	Australia	59
		Brazil	150
	Tribolium castaneum	Australia	58, 59
Dichlorvos	*Sitophilus granarius*	Serbia	107, 108, 109
	Liposcelis bostrychophila	China	69
		United States	69
Etrimfos	*Oryzaephilus surinamensis*	England	186
Fenitrothion	*Oryzaephilus surinamensis*	Australia	94
		Wales	34
Malathion	*Sitophilus oryzae*	Egypt	30
	Sitophilus granarius	Serbia	107, 108, 109
	Sitophilus zeamais	Brazil	85, 150
		Mexico	143
	Tribolium castaneum	Belgium	22
		France	22
		Ivory Coast	91
		United Kingdom	22, 91
	Tribolium confusum	Israel	91
Pirimiphos-methyl	*Cryptolestes ferrugineus*	India	48
	Oryzaephilus surinamensis	Australia	94
		England	186
		Wales	34
	Sitophilus granarius	Serbia	107
	Sitophilus zeamais	Brazil	85, 150
		Mexico	142
	Tribolium castaneum	Egypt	30

(Continued)

Table 2 *(Continued)*

Contact insecticides	Insect species	Country of resistance detection	Reference(s)
Oxadiazine			
Indoxacarb	*Sitophilus zeamais*	Brazil	87
Pyrethroids			
Bifenthrin	*Rhyzopertha dominica*	Australia	68
Cyfluthrin	*Tribolium castaneum*	United States	175
Cypermethrin	*Sitophilus granarius*	Serbia	108, 109
		Brazil	86, 150
Deltamethrin	*Cryptolestes ferrugineus*	India	48
	Rhyzopertha dominica	Australia	64
		Taiwan	52
		Brazil	118, 119
	Sitophilus granarius	Serbia	108, 109
	Sitophilus zeamais	Brazil	86, 150
		Mexico	143
	Tribolium castaneum	Australia	55
Permethrin	*Sitophilus oryzae*	Pakistan	103
	Sitophilus zeamais	Brazil	86, 150
		Mexico	143
	Oryzaephilus surinamensis	England	186
	Liposcelis bostrychophila	United Kingdom	5
Phenothrin	*Cadra cautella, Oryzaephilus surinamensis, Rhyzopertha dominica, Sitophilus oryzae, Sitophilus zeamais, Tribolium castaneum*	Australia	59

Compounds within a specific chemical group usually share common target sites in insects and thus share a common mode of action, and generally, development of resistance is based on a genetic modification of this target site. When this occurs, the compound loses its pesticidal efficacy, and cross-resistance occurs when resistance to a given pesticide confers resistance to another pesticide without the insect having been exposed to the latter pesticide (160). A good example of cross-resistance is the development of resistance in *R. dominica* to the whole group of organophosphates after the initial development of resistance to malathion (68, 85).

Resistance Mechanisms

The complete mapping of the *T. castaneum* genome provided an excellent tool for biologists to address numerous topics (177), including the genetic basis of pyrethroid resistance (194). Three major resistance mechanisms have been the focus of research: metabolic resistance, target site resistance/insensitivity, and reduced cuticular penetration resistance. Metabolic resistance is the most common mechanism that insects use to detoxify or metabolize an insecticide by producing higher amounts of enzymes (e.g., cytochrome P450–dependent monooxygenases, hydrolases, or glutathione-*S*-transferases) (41, 53, 79, 80, 87, 147). The target site resistance/insensitivity mechanism interferes with the attachment of the insecticide molecule to the target site [e.g., voltage-gated sodium channels and gamma-aminobutyric acid (GABA) receptors] in the insect's central nervous system (41, 56, 136, 147, 165). This mechanism includes the (*a*) altered acetylcholinesterase resistance (ACHR) mechanism, providing resistance to organophosphates

and carbamates; (*b*) knockdown resistance (*kdr*) mechanism, conferring resistance to DDT and pyrethroids; (*c*) reduced GABA receptor sensitivity mechanism, causing resistance to phenylpyrazoles and cyclodienes; and (*d*) altered nACHRs, which provides resistance to neonicotinoids (103, 120, 138, 155, 156, 165, 167, 185, 191). The reduced cuticular penetration resistance mechanism is considered uncommon, which helps reduce the dose of the insecticide reaching into the insect's body and can occur when an insect develops a cuticular barrier by altering the cuticular thickness or by changing the cuticular composition. For example, several cuticular proteins (TcCPR18, TcCPR4, and TcCPR27) are associated with the formation of a rigid cuticle in *T. castaneum* (135).

Resistance Management

Opit et al. (136) have explained key principles of a tactical resistance management strategy that relies on three major components: (*a*) information about the storage system, particularly the infestation pattern, including strength and frequency of resistance; (*b*) tactics that reduce the rate of selection (e.g., reducing the frequency of use of the same chemistry, cooling, chemical and physical hygiene); and (*c*) tactics that destroy resistant insects and eliminate resistance foci [e.g., alternative chemicals (protectants or fumigants), physical methods such as heat disinfestation]. The following three practical steps have helped industry mitigate several resistance problems across the globe.

Early detection through monitoring. Well-developed published bioassay methods are available for the early detection of resistance development in SPPs (49, 50, 58, 76). These include methods that utilize a diagnostic concentration of chemicals for topical application, expose adult insects to insecticide-impregnated filter paper, or directly spray an insecticide on test insects to provide indicative results on resistance within a short time frame of 5 to 20 h. However, although time-consuming (2–6 weeks), bioassays involving grain admixtures and structural treatments can reveal the potential of a pesticide for facilitating long-term protection from the target species by measuring its residual toxicity against both adults and immature stages at different time intervals (62, 126).

Rotation of treatments to minimize application and reduce selection. In an IPM strategy, pesticides that share cross-resistance should be avoided, and the failure to do so expedites the development of resistance. Ideally, two or more pesticides with different modes of action should be rotated, so that the period of selection of any pesticide does not extend beyond one generation, and coordinated over a large area so that insects functionally belonging to the same gene pool are not simultaneously selected for resistance to the different pesticides used in the rotation (65, 136).

Use of different chemistries in combination to control multiple resistances across SPPs. As discovery of new treatments is rare and registering them is a costly and time-consuming option, combinations have long been used by industry to maximize the potential of available chemistries by considering how many species and resistant types within species can be controlled. Several mixtures have been successfully evaluated and are being used by industry in Australia to combat multiple resistance problems across a broad spectrum of SPPs (58, 128, 133). The most effective combinations evaluated were spinosad and chlorpyrifos-methyl, which controlled all strains except the organophosphorus-resistant *O. surinamensis*, and chlorpyrifos-methyl and S-methoprene, which controlled all strains except the methoprene-resistant *R. dominica* (58). To achieve complete success in controlling the resistant pest spectrum, spinosad is currently being applied in Australia in a tertiary combination with chlorpyrifos-methyl and S-methoprene (133). Other examples of combined treatments that have been investigated include synergized bifenthrin and chlorpyrifos-methyl against several beetles and psocid species (68), diflubenzuron and methoprene against *S. oryzae* and *R. dominica* (67), spinosad and chlorpyrifos-methyl against psocids (128),

chlorpyrifos-methyl and deltamethrin against psocids (24), methoprene and synergized pyrethrin against *T. castaneum* (178), spinosad and chitin synthesis inhibitors against *S. oryzae* (89), and abamectin and deltamethrin in combination with DE and kaolin against *T. granarium* (88).

CHALLENGES AND OPPORTUNITIES FOR SUSTAINABLE USE OF CONTACT INSECTICIDES

As discussed in the preceding sections, the scientific literature shows that diverse synthetic chemicals and chemicals derived from natural sources have been investigated over several decades as potential treatments for controlling SPPs. Why, then, have so few investigated chemicals received wider adoption by industry? In this section we analyze the opportunities and barriers to adopting potentially new contact insecticides. The factors influencing the adoption or likely adoption of a newly discovered chemistry fall under four broad categories: biological, technical, legal, and commercial (65). Biological factors include the mode of action of chemicals and the susceptibility of different species to resistance development; technical factors such as availability of appropriate application technology and industry requirements, including maximum residue levels (MRLs), are critical. Prior to the registration of a new treatment, important legal and commercial drivers include willing registrants, trade requirements, consumer sensitivity to insecticide residues in food, and occupational health and safety concerns.

Renewed Interest in Contact Insecticides due to Resistance to Phosphine

Two major reasons for industry's renewed interest in the use of contact insecticides in postharvest commodity protection are the global phasing out of the key fumigant methyl bromide due to its ozone-depleting nature and the increasing trend in resistance development in major SPPs to the dominant fumigant phosphine (132). The absence of suitable alternative fumigants matching the positive attributes of methyl bromide and phosphine has worked in favor of contact insecticide use. While the global registration of the biopesticide spinosad as a grain protectant during the past decade (95) has been a standout example of the continued use of contact insecticides, the recent development of another biopesticide, flavesone, as a potential grain protectant in Australia reflects the future dependency of the grain industry on the role of contact insecticides in the management of SPPs (61). Moreover, ongoing use of contact insecticides in combinations in Australia (e.g., an organophosphate, S-methoprene, and spinosad) demonstrates industry's capacity to combat resistance problems in postharvest commodity protection (133). Despite the lack of support from registrants for the commercialization of contact insecticides for legal use by industry, there have been discoveries and developments of new molecules through rigorous research and development across the globe. Examples of such compounds that have been extensively evaluated in the laboratory but not progressed to wider industry adoption include bifenthrin (68), diflubenzuron (67), ethiprole (a phenyl-pyrazole) (9), imidacloprid (a neonicotinoid) (63), thiamethoxam (a neonicotinoid) (21), and indoxacarb (an oxadiazine) (63).

Consumer Awareness and Sensitivity to Insecticide Residues in Food

Over the last two decades, extensive media coverage, general education, and a growing concern for health have driven global consumer awareness of pesticide residues in food and the environment to a new high (38). This ongoing trend in consumer scrutiny has directly influenced policy development and industry adoption of safer pest management practices. For example, the European Food Safety Authority publishes an annual report on pesticide residues in food on the European market, ensuring that the prevailing health risk to EU consumers remains low, and more than 90% of samples screened met MRLs (71). While high standards of milling,

baking, malting, and brewing are practiced in developed countries, serious challenges from chemical residues still exist for specific products, such as baby food, which legally requires MRLs significantly lower than those for grain and other processed food products (32, 33, 142). Increased consumer awareness also created opportunities for research and development on nonchemical (e.g., microbial, heat, modified atmospheres) and integrated methods for controlling SPPs. However, excessive consumer sensitivity can negatively affect the way SPP problems are managed, particularly when only a few active ingredients are available and there is an upward trend in the development of resistance to pesticides in key SPPs and in its spread across continents, posing risk to the sustainability of currently registered treatments (1).

Workplace Health and Safety Restrictions Related to the Use of Fumigants

Although fumigation of grain bins is a valid component of management plans for SPPs, the process poses inherent dangers that could lead to the substitution of grain protectants for fumigants. Entering a grain bin involves risks to workers, including but not limited to hazards associated with confined space entry, dust inhalation, and grain engulfment (36). A detailed management plan is required for undertaking fumigation, including sealing the storage structure, applying the fumigant, monitoring the gas concentration, and postfumigation venting to minimize exposure to workers and bystanders who may be present in the environment surrounding the fumigated structure (39). In some cases, industry regulations restricting bin access may necessitate introducing fumigants from outside the bin, including at ground level (70). Finally, there is a potential risk of fire or exposure hazards from grain dust, uneven distribution of the fumigant during the application process, or combustion due to excess moisture in the grain (114).

Increasing Costs of Developing and Registering New Chemistries

The cost of research, development, and registration of a new neurotoxic insecticide has risen from \$50–100 million in the 1990s (47) to estimates approaching \$250 million today (54, 144, 170). Thus, it may be unlikely that a new insecticide will be registered easily, specifically for managing SPPs, due to the cost of registration and the infrequent use compared to that for insecticides used in other agricultural systems such as field crops. The registration process for insecticides developed as grain protectants that are directly applied on grains follows stricter guidelines, which include a series of environmental monitoring data, that may not be required for the registration of other biocides (74, 171). In short, insecticides used in postharvest commodity protection are generally considered a niche market, and the overall cost of their application is not always regarded through an economic threshold model (101).

Complex and Strict Regulatory Requirements for Insecticide Residues in Global Trade

A certain level of regulatory requirements and standards for insecticide residues in global trade is essential for ensuring food safety. International standards, such as those established by the Codex Alimentarius Commission, set MRLs that are originally intended to harmonize pesticide safety thresholds in countries across the globe, aiming to prevent trade barriers and support international trade in agricultural commodities. However, several countries, multinational commodity traders, and food retailers (supermarket chains) enforce their own, often more stringent regulations, creating a complex landscape of compliance standards (105, 145). For example, the European Union enforces some of the strictest MRLs, particularly for pesticides such as specific organophosphate insecticides used to control SPPs (74, 75, 168, 184). This situation may change soon due to global warming, which has been implicated in the movement and establishment of

major SPPs in certain European countries that never recorded these pests before (1). Differences between national regulations and international standards can lead to trade disputes, increased costs, and additional efforts to meet diverse market requirements, which can pose a major challenge for producers and exporters that are forced to navigate a complex regulatory landscape to comply with both international guidelines and country-specific requirements. This regulatory complexity extends back to the farm level, where farmers and commodity storage operators must adjust their insecticide programs for commodity protection against SPPs to align with the strictest regulatory requirements of target markets.

CONCLUSION

This review highlights the importance of contact insecticides in stored-product protection from various SPPs that have significant economic, social, and environmental impacts. Certainly, the grain industry has witnessed a significant change in the landscape of SPP management over the last three decades, since a major review by Arthur (7) on contact insecticides. Since then, several conventional active ingredients have been deregistered due to the widespread development of resistance in major SPPs, economic costs associated with reviews and reregistration, and pressure from consumers and environmental movements. Although thousands of plant-derived materials and DE products are being developed, only a few have been registered and are useful only on small-scale farms. The grain industry is left with few active ingredients, and to add to this problem, development of resistance to the widely used fumigant phosphine in major SPPs is increasing across the globe. Developed countries, including Australia, which has serious resistance problems, are utilizing existing contact insecticides by strategically using them in combination and as phosphine resistance breakers through the adoption of an IPRM program. Stored-product protection from insects remains a major focus across continents from socioeconomic and political points of view due to the increasing requirement of food for an expanding global population. In this scenario, we conclude that for the foreseeable future, contact insecticides will continue to play a critical role in protecting postharvest food grains and processed products during storage.

FUTURE ISSUES

1. Global monitoring of resistance in major stored-product pests (SPPs) to currently registered contact insecticides, using harmonized bioassay methods and molecular diagnostics, to establish the strength and spread of resistance is a priority. A global resistance survey is long overdue, as the first and the only survey was undertaken in 1976.

2. Optimization of an integrated pest and resistance management decision-making system and its global implementation are needed that incorporate a monitoring program for early detection of resistance to currently registered contact insecticides, timely interventions through use of suitable alternatives to control resistance, and their evaluation.

3. Global effort should continue to develop novel environmentally friendly, reduced-risk chemistries as alternatives to currently registered insecticides that aim to control a broad-spectrum of SPPs and their field validation, with a strong real-world focus with end-user needs in mind.

4. Numerous natural origin-based products with established preliminary efficacy data should be analyzed through large-scale field trials to explore the most-promising

candidates for their potential registration as stand-alone treatments or in combination with currently registered contact insecticides.

5. Currently registered contact insecticides used against pests of field crops and orchards should be reviewed to short-list potential candidate materials and to generate required efficacy data against SPPs in order to extend their current registration to postharvest commodity protection—an approach that may save millions of dollars.

6. Global collaborative research is needed to evaluate the efficacy of contact insecticides against important emerging, invasive, or quarantine SPPs [e.g., psocids; khapra beetle, *Trogoderma granarium*; larger grain borer, *Prostephanus truncatus* (Horn)], updating and harmonizing existing phytosanitary/biosecurity protocols relevant to domestic and international trade.

7. Research-driven generation of scientific data and professional advice are critical to establishing global uniformity in regulatory requirements in trade for maximum residue levels (including cumulative residues) in grain and processed food for currently registered and upcoming active ingredients of insecticides.

DISCLOSURE STATEMENT

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