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Review

Prospects for Use of Biological Control of Insect and Mites for the Food Industry in North America

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Abstract: There are a number of strategies used to mitigate and control insect infestations in stored products and stored product facilities in North America and globally. Fumigation remains one of the main techniques used, particularly in bulk grain. Other techniques are also utilized effectively, such as the use of extreme temperatures and the use of biological control agents, but are mainly restricted to organic products and to Europe, respectively. Here, we review the past research conducted in the field of biological control for pests of stored products in North America and in Europe, its past and present successes in Europe, its challenges, and what we can learn from them to develop biological control as a viable option to problems of insect pests of stored products in North America.

Keywords: natural enemies; postharvest; stored products; food facilities; integrated pest management; insects; parasitoids; predators; regulations

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1. Introduction

The use of beneficial arthropods for controlling infestations of insects and mites in stored products, processing facilities and warehouses has undeniable benefits. It is innocuous to humans, is sustainable, and is an additional tool for controlling pests in a field with too few available pesticides and increasing resistance of pests to those pesticides [1]. Since stored product environments are enclosed, biological control options are restricted to augmentative biological control, whereby natural enemy populations are supplemented to achieve desired control [2]. Over the last two decades, the adoption of augmentative biological control in general has increased in Europe, Asia and Latin America as a result of political developments helped by demand of retailers, consumers, and non-governmental organizations [3,4]. The commercialization and use of beneficial insects for stored product environments is well-established in Central Europe. Commercialization of a predatory mite, *Cheyletus eruditus* (Schrank), for the biological control of stored food mites was initiated in Czechoslovakia in 1983 [5–7], and in 1997 a company specializing in the marketing of biological control agents for the food product industry was established and has since proven to be an effective and viable practice [8]. This practice is increasingly growing in popularity in Central Europe, now with suppliers in Germany, Austria and Switzerland. However, despite research efforts conducted in the USA over the last three decades [1], this practice has not taken off in North America. There has, however, been a failed attempt at commercialization of beneficial insects for stored product pests in the USA at the beginning of the 21st century. We can only guess why this attempt did not last but the root of the problem may have been the general lack of knowledge of beneficial insects and of biological control by stakeholders and consumer populations of North American countries compared to European countries [9], with consumers not accepting that insects be associated with food products and manufacturers unwilling to risk consumer complaints or to fail an inspection if “insects” are found in the facilities. Instead, there is a high reliance on fumigation and insecticides to control pests of stored products.

However, there is great concern regarding the reliance on phosphine gas (i.e., hydrogen phosphide—PH_3) as the main—and often the sole—way of controlling insect infestations, particularly in bulk storage of stored products in North America and globally, which has been relied upon for decades [10–13]. Its ubiquity, and often suboptimal deployment, has led to the development of multiple resistance strains among all the main stored product pest species in many countries [14–18]. There are currently no economically viable, equally effective alternatives to phosphine. Therefore, despite its decreasing efficacy, it continues to be heavily used.

In North America, as in the rest of the world, consumers are increasingly looking for natural products, lower inputs, and natural production practices. Biological control therefore seems like an increasingly suitable solution to insect problems. However, the past North American attempt, and the European success, shows that its development in North America should be accompanied with communication to consumers and to food processors, and that additional research, particularly investigating how to successfully use beneficial agents in bulk grain, will need to be conducted.

2. Available Management Techniques

2.1. Preventing Infestations

The primary objective when storing food commodities is to prevent spoilage and infestations before they occur, thereby avoiding the necessity of implementing control strategies. The first fundamental step toward this goal is to appropriately design structures and equipment for food storage and processing. To thrive, insects need food, warmth, harborage, and moisture. Eliminating all, or at least some, of these factors is the best way to keep insects at bay [19]. The next step toward this goal is good sanitation in and around storage and processing equipment, particularly between uses, as well as in and around storage and processing facilities. The third and fourth steps are regular inspections of the facility and commodities and monitoring the presence of pests with traps. The fifth step is to always follow good practices and avoid becoming complacent. It is not the goal of the current contribution to go into these items in any detail as there are publications that can be consulted to this effect [20–25].

These principles also apply to farm-stored grain, with the added constraint to bring the moisture content and temperature of freshly harvested commodity sufficiently low and in a timely manner to prevent proliferation of molds and pests. Even if the temperature and moisture content of harvested grain are at levels that show to be adequate on safe storage charts [26,27], changes in outside temperature throughout the year create convection currents within grain bins that induce migration of heat and moisture, toward the center in the fall and winter and toward the edges in the spring and summer, where hotspots—and therefore spoilage—can occur, so grain condition needs to be regularly monitored [26,28].

Biological control cannot replace the above-stated measures. Biological control may be used to replace techniques to kill insects when there are signs of infestations, or to maintain pest populations at low levels before regulatory-specified tolerances.

2.2. Controlling Infestations

If an insect infestation occurs, one or multiple control methods will be implemented. A number of options are currently available, including manufactured chemical products and natural products. To reduce the insect presence in or around storage structures and processing facilities it is common practice to apply residual insecticides (e.g., malathion, pyrethrins, cyfluthrin) or other products (e.g., diatomaceous earth, insect growth regulators) to treat cracks and crevices, for spot treatment, to sanitize empty bins, or as general treatment of floors, walls, ceilings, and outside areas [29,30]. To control infestations in stored grain and storage structures in North America, fumigation is typically used, but sometimes the use of modified atmospheres (i.e., naturally or artificially increasing the concentration of a common gas in the atmosphere, typically CO_2 or N_2, to lethal levels) or extreme temperatures are implemented. The most commonly used fumigant to kill insects in grain in North America and around the world is phosphine gas, because of its low cost and convenience of use [10,13].

Unfortunately, decades of intensive use of fumigants and other insecticides coupled with their suboptimal use (e.g., leakages from structures inadequately gas-proofed, loss of permeability of gas-proof sheet after repeated uses, gas concentration rarely monitored over the fumigation period) has been linked to the development of resistance of all the main stored product insect pest species to phosphine, malathion, and other now-banned products across the world [15,31,32]. Resistance is either considered weak (i.e., individuals die when exposed to recommended levels of products after a lag) or strong (individuals survive recommended levels). An increasing number of stored product pest species are found to display strong resistance to phosphine [33]. In Australia, a strain of *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Laemophloeidae) with strong resistance to phosphine gas was found to displayed resistance factors of 560 to 1458 times that of a susceptible strain [17]. With the delisting of once popular and effective fumigants, such as methyl bromide, there are now few alternatives to phosphine gas. Sulfuryl fluoride is an alternative, but it is more difficult to use and could face deregulation since it was found to be a greenhouse gas 4800 times more potent than carbon dioxide [34]. Stored product insects are also known to have developed resistance to insecticides used for space treatment and product disinfection [15,16].

Beside pest resistance, other aspects make the use of insecticides and fumigants decreasingly appealing such as the risk of residues in food products, even when the pesticides are not used directly onto the products [35,36], the risk of exposure to applicators, possible issues with metal corrosion and self-ignition of phosphine gas, and the continuous increase in organic farming production and increasing demand in North America for organic products throughout the supply chain [37]; i.e., the number of certified organic farms increased by 50% in USA between 2008 and 2019 and by 45% in Canada between 2009 and 2019 [38], which is in great need of non-chemical alternatives.

3. Regulation of Biological Control in Stored Products in USA and Canada

In the US, the Environmental Protection Agency (USEPA) published a rule governing biological control in the early 1990s allowing the release of parasitoids and predators into food facilities [39], Table 1. The same rule also relegated beneficial organisms after harvest to regulation by the Federal Insecticide Fungicide and Rodenticide Act (FIFRA), while exempting it from the requirement of federally mandated tolerances in food products. More specifically, the USEPA exempted all genera of parasitoids and predators known to commonly attack stored-food insects from counting towards tolerances in stored raw whole grains and packaged food in warehouses so long as the insects do not become a component of the food. Even after the rule's publication, the US Food and Drug Administration (USFDA) continued to use federally mandated criteria for enforcement of insect fragments in food [40], while the US Federal Grain Inspection Service (USFGIS) is responsible for maintaining compliance, including inspecting and grading the grain.

Table 1. Regulations regarding biocontrol agents and adulteration of stored products with insects in the USA and Canada.

Regulation	Explicitly Mentions Biocontrol Agents?	Applicable Text or Description
USA:		
40 CFR §180.1101 Parasitic (parasitoid) and predatory insects; exemption from the requirement of a tolerance [39]	Yes	"Parasitic (parasitoid) and predatory insects are exempted from the requirement of a tolerance for residues when they are used in accordance with good agricultural and pest control practices to control insect pests of stored raw whole grains such as corn, small grains, rice, soybeans, peanuts, and other legumes either bulk or warehoused in bags. For the purposes of this rule, the parasites (parasitoids) and predators are considered to be species of Hymenoptera in the genera *Trichogramma*, Trichogrammatidae; *Bracon*, Braconidae; *Venturia, Mesostenus*, Ichneumonidae; *Anisopteromalus, Choetospila, Lariophagus, Dibrachys, Habrocytus, Pteromalus*, Pteromalidae; *Cephalonomia, Holepyris, Laelius*, Bethylidae; and of Hemiptera in the genera *Xylocoris, Lyctocoris*, and *Dufouriellus*, Anthocoridae. Whole insects, fragments, parts, and other residues of these parasites and predators remain subject to 21 U.S.C. 342 (a) (3)".
21 U.S.C. §342 Adulterated food (a) [41]	No	Governs what constitutes adulterated food in the USA; "A food shall be deemed to be adulterated . . . if it consists in whole or in part of any filthy, putrid, or decomposed substance, or if it is otherwise unfit for food; or if it has been prepared, packed, or held under insanitary conditions whereby it may have become contaminated with filth, or whereby it may have been rendered injurious to health; or if it is, in whole or in part, the product of a diseased animal or of an animal which has died otherwise than by slaughter; or if its container is composed, in whole or in part, of any poisonous or deleterious substance which may render the contents injurious to health". According to 40 CFR §180.1101, "Whole insects, fragments, parts, and other residues of these parasites and predators [i.e., species listed in 40 CFR §180.1101]" are subject to this regulation. 21 U.S.C. §342 concerns finished foods while 40 CFR §180.1101 concerns raw whole grains.
Food Safety Modernization Act (FSMA) of 2010 [42]	No	Improved food safety in the USA by requiring food safety plans, even after harvest, and making current good manufacturing practices standard instead of optional along with a host of other changes. Did not overwrite exemption for biocontrol agents, but dramatically changed food safety culture in the pre- and post-harvest supply chain.
US Grain Standard Act of 1916. Subpart A—General Provisions [43]	No	Defines what constitutes infested grain: "These grains will be considered infested if the representative sample (other than shiplots) contains two or more live weevils, or one live weevil and one or more other live insects injurious to stored grain, or two or more live insects injurious to stored grain". Beneficial insects rarely kill 100% of pests so this tolerance can reassure potential users of beneficial insects in bulk grain.
CPG Sec. 578.450 Wheat Flour-Adulteration with Insect Fragments and Rodent Hairs [44]	No	Defines acceptable limit of insect fragments in wheat flour as "an average of 75 or more insect fragments per 50 g".
Food Defect Action Levels [40]	No	This document lists acceptable limits of insect's fragments in foodstuff.
Plant Protection Act of 2000 [45]	Yes	This legislation regulates the importation, shipping, and release of non-native or non-widely distributed biological control agents in the US from abroad or among state lines. Regulations are enforced by USDA APHIS PPQ.
Canada:		
Canada Grain Act of 1985 [46]	No	Defines infested grain: "infested means containing any injurious, noxious or troublesome insect or animal pest". Grain containing beneficial insects should therefore not be considered infested. However, it also means that there is no tolerance for the presence of any injurious pest in grain, which limits the attractiveness of biocontrol in bulk grain because it is unlikely to eliminate 100% of the pests.
Canadian Grain Regulations [47]	No	Lists thresholds for "matter other than cereal grains" and "foreign material" for Canadian grain.

Table 1. *Cont.*

Regulation	Explicitly Mentions Biocontrol Agents?	Applicable Text or Description
Official Grain Grading Guide (Canadian Grain Commission) [48]	No	Lists thresholds for insect parts in Canadian grains destined for exportation. Defined insect parts as: "pieces of insects such as grasshoppers and lady bugs that remain in the sample after cleaning or processing. Samples are analyzed for the percentage of insect fragments and graded according to established tolerances. If pulse crops come into contact with insects during the harvesting process, it may result in seed staining and earth adhering to the seed and may result in samples having an objectionable odour. Samples containing staining of this nature will be considered to be earth tagged and graded according to colour definitions. Samples having a distinct objectionable odour not associated with the quality of the grain will be graded Type of Grain Sample Account Odour". Insect staining and odour being mainly an issue in pulses because they are typically less processed than other grains, thresholds for insect parts are only listed for pulses. For other grains, insect parts would fall under "matter other than cereal grains" or "foreign material". However, due to the nature of biocontrol agents which have small and fragile bodies, they would likely not be found in cleaned grain or well within acceptable limits.
Food and Drugs Act of 1985 [49]	No	Governs what constitutes unsanitary food in Canada: "Unsanitary conditions means such conditions or circumstances as might contaminate with dirt or filth, or render injurious to health, a food, drug or cosmetic".
Safe Food for Canadians Regulations [50]	No	This regulation states that: "(51) (2) An animal must not be in a facility or conveyance where a food is manufactured, prepared, stored, packaged or labelled or where a food animal is slaughtered, unless the animal is (c) an animal that is intended to be used in the manufacturing or preparing of a food in the facility or conveyance"; and "51 (3) Any measures that are taken for the purposes of complying with subsections (1) and (2) must not present a risk of contamination of a food". Contaminated food is defined as: "the food contains any micro-organism, chemical substance, extraneous material or other substance or thing that may render the food injurious to human health or unsuitable for human consumption, including those that are not permitted under the Food and Drugs Act or those that do not comply with any limits or levels provided under that Act".
Guidelines for the General Cleanliness of Food [51]	No	This document lists acceptable limits of insect's fragments in foodstuffs.
Plant Protection Act of 1990 [52]	Yes	This legislation regulates the importation and overall movement of organisms, including biological control agents, to prevent the introduction and spread of pests in Canada.
Pest Control Products Act of 2002 [53]	No	Canadian act regulating the registration of products, including live organisms, for the control of pests.

In the early 2010s, food safety regulation was radically overhauled in the US with the passage of the Food Safety Modernization Act (FSMA) [42] in response to multiple large and widely covered outbreaks of food-borne illness in the US [54,55]. This has equally affected pre-harvest and post-harvest agriculture in the US, with radical shifts in the regulations governing both. FSMA defines a pest as "any objectionable animals or insects, including birds, rodents, flies, larvae". Most notably, FSMA transformed current good manufacturing practices (cGMPs) from simple guidance into requirements for food facilities. With the passage and enforcement of FSMA, the culture among both pre-harvest and post-harvest food facilities became one extremely concerned about potential contamination by any other living source that could potentially lead to a costly recall.

Importantly, according to the USFDA the passage of FSMA did not specifically address the use of biocontrol agents after harvest, nor did it change the existing 1992 USEPA rule exempting parasitoids and some predators from counting towards tolerances in bulk storage and bagged goods [56]. Nonetheless, anecdotally, there appears to be a common fear by stakeholders that releasing natural enemies at food facilities in the US would violate food safety regulations. This presents a strong cultural barrier that must be circumvented if biological control is to succeed in the US.

In Canada, there is no specific regulation pertaining to the use of biocontrol agents in stored products. Their use therefore falls under other regulations restricting the presence of insects and insect parts in commodities. The 1985 Canada Grain Act prohibits the commercialization of "infested grain". Grain is considered infested if it contains "any injurious, noxious or troublesome insect or animal pest". Therefore, grain containing biological control agents should not be considered infested. Since there is no exception from the requirement of a tolerance for residues for biocontrol agents in Canada, the use of these organisms would have to comply with limits for insect parts in grain and grain products [48,51], Table 2. The use of biocontrol agents in stored products and stored product environments in Canada should also comply with the Safe Food for Canadians Regulations as detailed in Table 1 [57].

Table 2. Tolerances for live insects in grain, insect fragments/parts in grain and wheat flour, and damaged kernels, in USA and Canada.

Presence of Insects/ Insect-Damaged Grain	Country	
	USA	Canada
Live and dead biological control agents in raw whole grain	Parasitic (parasitoid) and predatory insects are exempt from the requirement of a tolerance [39], Table 1.	No exemption of a tolerance.
Live pest insects in grains	A representative sample (1000 g), a shiplot sample (500 g/2000 bushels), a lot as a whole (stationary), or an online sample (e.g., railcar) is considered infested if: For wheat, rye, and triticale: it "contains two or more live weevils, or one live weevil and one or more other live insects injurious to stored grain, or two or more live insects injurious to stored grain". For barley, canola, corn, oats, sorghum, soybeans, sunflower seed, and mixed grain: it "contains two or more live weevils, or one live weevil and five or more other live insects injurious to stored grain, or ten or more live insects injurious to stored grain" [43,58].	For "any seed designated by regulation as a grain for the purpose of this Act" (i.e., the Canada Grain Act), receipt and marketing of contaminated grain (i.e., grain containing any injurious, noxious or troublesome insect or animal pest) is prohibited [46].
Insect fragments in grain	In peas and beans: "average of 5% or more insect filth by count insect-infested and/or insect-damaged by storage insects in a minimum of 12 subsamples". For wheat and other grains, maximum limits for insect parts are not mentioned and would fall under "foreign material", which is variable between grain types and grades [40].	Maximum limit of 0.02% insect parts (by weight) in pulses. For wheat and other grains, maximum limits for insect parts are not mentioned and would fall under "matter other than cereal grains" and "foreign material", which are variable between grain types and grades, but insect parts are not a real issue in those commodities [51].
Insect damaged kernels	In wheat: maximum of 31 insect-damaged kernels (IDK) per 100 g of wheat (in dockage-free and shrunken and broken-free portion of wheat). In other grains, tolerance for insect-damaged kernels are included within "damaged kernels", which is highly variable (2% to 20% depending on grain type and grade) [40,58].	For wheat, kernels damaged by indianmeal moth are included in the grading factor "degermed kernels (DGM)". Kernels damaged by other insects (except sawfly and midge) are considered "Insect damage (I DMG)". Maximum limits of degermed kernels in wheat vary from 4% (No. 1 grade) to 13% (No. 3 or No. 4 grade) depending on wheat type. Tolerance for damaged kernels vary from "reasonably free from damaged kernels" (No. 1 grade) to "reasonably free from severely damaged kernels" or "moderately free from severely damaged kernels" (other grades). In pea, fababean and sunflower the maximum amount of insect damaged seeds is between 1% and 4% depending on grain type and grade. In other grains, insect-damaged seeds are included within "damaged seeds", which is highly variable (from 0.5% to 25% depending on grain type and grade) [48].

Table 2. *Cont.*

Presence of Insects/ Insect-Damaged Grain	Country	
	USA	Canada
Insect fragments in wheat flour	Considered defective when six 50 g subsamples are found to have an average of 75 or more insect fragments [44].	A lot is considered defective if at least one of three samples contain more than 50 insect fragments (≤0.2 mm) per 50 g or if at least two of three samples contain more than 20 insect fragments (≤0.2 mm) per 50 g, pre-milling; and when one of three samples contain more than 20 insect fragments (>0.2 mm) per 50 g or when two of three samples contain more than 20 insect fragments (>0.2 mm) per 50 g, post-milling [51].

4. Availability of Biocontrol Agents in Europe and in North America for Stored Products

Whereas in Europe a number of biocontrol agents are available for use against pests of stored products (Table 3), as of 2002, such biocontrol agents were not commercially available in North America [59], and as of today still none are available, except for one species that may be considered an exception. However, sometime between 2002 and about six years ago some biocontrol agents specifically targeting pests of stored products were commercially available in North America. A 1997 list of suppliers of beneficial organisms in Mexico, USA, and Canada (Hunter 1997) lists five suppliers commercializing at least one beneficial organism specifically targeting a pest of stored products; i.e., *Anisopteromalus calandrae* (Howard) (Hymenoptera: Pteromalidae), *Habrobracon hebetor* (Say) (Hemenoptera: Braconidae), *Pyemotes tritici* (LaGrèze-Fossat and Montagné) (Trombidiformes: Pyemotidae), and *Xylocoris flavipes* (Reuter) (Hemiptera: Lyctocoridae). Another list of suppliers of beneficial organisms in North America [60] shows that in 2010 there were only three suppliers still commercializing these organisms. We contacted the suppliers that used to commercialize beneficial organisms targeting pests of stored products on the 1997 and 2010 lists to inquire why they discontinued their commercialization. One supplier (Biofac, Mathis, TX, USA) informed us that they stopped producing beneficial organisms and switched their activity to commercialize a fertilizer, for economic reasons. Two suppliers did not actually rear these species themselves but acquired them from Biofac when needed. Two other suppliers had sold these organisms for such short periods and so long ago that they did not recall marketing them. One supplier had *H. hebetor* on its product list but did not directly sell it. Instead, they kept it listed for awareness that this species is commercially available elsewhere, and if somebody showed interest in acquiring it, they would redirect the client to contact Biofac. However, they have not received queries about *H. hebeor* in a long time and were not aware that Biofac had ceased its production. All the vendors contacted were asked how often they were contacted by clients interested in purchasing biocontrol agents for the control of stored product pests. Biofac indicated that biocontrol agents for stored product pests sold just as well as biocontrol agents from other systems they produced and sold, but the other vendors (i.e., those still involved with the commercialization of other beneficial insects) indicated that such queries were few and far apart. One vendor indicated that these requests were "certainly a lot less common in recent years than they were 15 years ago".

A screening of all biocontrol agents currently commercialized in North America revealed that one supplier, Anatis Bioprotection (Québec, Canada), currently markets *Trichogramma brassicae* Bezdenko (Hymenoptera: Trichogrammatidae) (under the name Tricho-mites®) for the control of stored product moths, indicating that it is "very effective at controlling food moths and clothes moths in homes, museums, businesses and industrial buildings. They can also be used as a treatment in bulk food stores, grain warehouses and flour mills". *Trichogramma brassicae* is widely commercialized in North America, Europe, and other parts of the world for the control of moth pests of vegetables but as far as we know there is no other vendor indicating pests of stored products as targets for this species. This shows that pest of stored products could be added to the list of targets of some commonly commercialized biocontrol agents, and this should be an easy step to implement, as long as it is supported by evidence for efficacy in the literature.

Table 3. Biocontrol agents commercialized against pests of stored products in Europe in 2021 [1].

Biocontrol Agent	Target	Place Commercialized
Anisopteromalus calandrae	Various Coleoptera	Germany
Apanteles carpatus	*Tineola bisselliella*	Germany
Baryscapus tineivorus	Cloth moths	Germany
Cephalonomia tarsalis	Various Coleoptera	Germany
Dinarmus basalis	Bruchinae	Germany
Habrobracon hebetor	Various Lepidoptera	Germany
Laelius pedatus [2]	*Anthrenus* spp. and *Trogoderma* spp.	Germany
Lariophagus distinguendus	Various Coleoptera	Austria, Germany
Spathius exarator	*Anobium punctatum*	Germany
Theocolax elegans	Various Coleoptera	Germany
Trichogramma evanescens	Various Lepidoptera	Austria, France, Germany, Switzerland
Venturia canescens [2]	Various Lepidoptera	Germany
Xylocoris flavipes	Various taxa	Germany

[1] Information mainly from JKI [61] and from vendors' websites mentioned therein. One vendor (Biologische Beratung GmbH) was contacted for up-to-date information. The species *Neoseiulus cucumeris* (Oudemans) (Mesostigmata: Phytoseiidae), *Stratiolaelaps scimitus* Berlese (Mesostigmata: Laelapidae), and *Trichogramma brassicae* are also commercially available in Europe but we did not list them here because vendors did not specify stored product pests as target organisms; [2] Species of Nearctic origin not displayed on the website of Biologische Beratung GmbH but can be made available for professional applications upon request.

Beside *T. brassicae*, there are other biocontrol agents currently commercialized for the control of non-stored product pests (e.g., horticultural pests) in North America, particularly of pest moths and mites that have been reported to attack certain species of stored product pests. These species therefore have the potential to be used against stored product pests. Table 4 lists beneficials currently commercialized in North America that have been reported to use pests of stored products as hosts or prey. However, further studies are needed, not only to demonstrate their efficacy on stored product pests but also to ascertain their association with stored product pest species. For example, a literature research revealed that most species reported as hosts of *Trichogramma* species listed in Table 4 were only found to be hosts in laboratory settings, often used as factitious hosts for the sole purpose of mass-rearing *Trichogramma* spp. *Trichogramma* are typically exposed to sterilized factitious host eggs in small vials so there is no evidence that these parasitoids can find these species' eggs from afar and that parasitism rates are satisfactory for biocontrol purposes. Furthermore, most reported parasitoid-host associations for North American *Trichogramma* spp. are doubtful, particularly those reported prior to 1930 [62]. There are currently 66 *Trichogramma* species reported from the Nearctic [63]. Due to little, or sometimes no, morphological differences among species, from 1871 to 1930 only one *Trichogramma* species was known in North America: *Trichogramma minutum* Riley (Hymenoptera: Trichogrammatidae) [62]. In 1951, the Hymenoptera of America North of Mexico Synoptic Catalog [64] listed four species of *Trichogramma* in North America and over 100 host species for *T. minutum* alone. We now know that *T. minutum* is a complex of two or more morphologically indistinguishable species within North America [65,66]. Much uncertainty still remains as to the real identity of many *Trichogramma* species and of their associated hosts [67]. Molecular-based identification combined with host-range testing will be necessary to clarify these questions and to effectively use *Trichogramma* species in biocontrol programs against stored product pests [68,69].

Table 4. Biocontrol agents commercially available in North America that are reported to use pests of stored products as their preys or hosts.

Biocontrol Agent	Stored Product Hosts/Preys *	References for Host/Prey Association
Neoseiulus cucumeris (Oudemans) (=*Amblyseius cucumeris* Oudemans)	Acari: *Acarus siro*	[70]
Orius insidiosus (Say)	Lepidoptera: *Ephestia elutella*, *Ephestia kuehniella*, *Plodia interpunctella*	[71–73]
Stratiolaelaps scimitus Berlese (=*Hypoaspis miles* (Berlese))	Acari: *Acarus siro*	[74]
Trichogramma brassicae Bezdenko (=*Trichogramma maidis* Pintureau and Vœgelé) [6]	Lepidoptera: *Cadra cautella* [2], *Ephestia kuehniella*, *Galleria mellonella* [2], *Nemapogon granella* [1], *Pectinophora gossypiella* [2], *Plodia interpunctella* [1,2], *Pyralis farinalis* [1], *Sitotroga cerealella* [3], *Tinea pellionella* [1]	[63,71]
Trichogramma minutum Riley	Lepidoptera: *Acrobasis caryae* [4], *Acrobasis vaccinia* [4], *Cadra cautella* [4], *Corcyra cephalonica* [4], *Cydia caryana* [5], *Cydia latiferreamus* [5], *Cydia nigricana* [5], *Ephestia kuehniella* [3], *Etiella zinckenella* [4], *Galleria mellonella* [3], *Pectinophora gossypiella* [4], *Phthorimaea operculella* [3], *Plodia interpunctella* [4], *Sitotroga cerealella* [2]	[63,71]
Trichogramma ostriniae Pang and Chen	Lepidoptera: *Corcyra cephalonica* [3], *Cadra cautella* [3], *Sitotroga cerealella* [3], *Ephestia kuehniella* [3], *Galleria mellonella* [3]	[63]
Trichogramma platneri Nagarkatti [7]	Lepidoptera: *Amyelois transitella*, *Cadra cautella* [3], *Cryptoblabes gnidiella* [2], *Ephestia kuehniella* [3], *Plodia interpunctella*, *Sitotroga cerealella* [3]	[63,67]
Trichogramma pretiosum Riley	Lepidoptera: *Acrobasis vaccinii*, *Amyelois transitella*, *Cadra cautella*, *Corcyra cephalonica* [3], *Ephestia kuehniella* [3], *Galleria mellonella* [3], *Pectinophora gossypiella*, *Phthorimaea operculella* [3], *Plodia interpunctella*, *Sitotroga cerealella* [3]	[63,71]

* Host species without a footnote indicate existing literature showing evidence of parasitoid-host association in natural conditions. [1] Successful control mentioned on the website of a beneficial agent supplier (Anatis Bioprotection). [2] Original references citing parasitoid-host association used hosts in laboratory studies, with no evidence found that parasitoids can parasitize them in natural settings. [3] Original references citing parasitoid-host association used factitious hosts for laboratory rearing, with no evidence found that parasitoids can parasitize these hosts in natural settings. [4] Original references prior to 1963, therefore parasitoid-host association is assumed incorrect. [5] Information from Hagstrum et al. [71], which did not provide sources for these reports. [6] A number of host records for *T. brassicae* may in fact have come from *T. evanescens* since the two species have been synonymized by previous authors, and there is some confusion about the identity of this species and similarities with other *Trichogramma* species [67]. [7] This species is morphologically identical to *T. minutum*.

Similar questions can be asked about other parasitoids of pests of stored products. For example, both *Theocolax elegans* (Westwood) and *Anisopteromalus calandrae* (Howard) (Hymenoptera: Pteromalidae) were described in the 1800s when parasitoid biodiversity was poorly known and their association with many host species originate from single publications where no proofs of identification are provided. Elucidating these fundamental questions will be a cornerstone for establishing sustainable and successful biological control programs.

5. Past Successes and Failures of Biocontrol of Pests of Stored Products in North America

Prior researchers have spent much of their careers in the US developing applied biological control programs for stored product insects. Over a period of decades, this has included both foundational studies on interacting components affecting biological control [75–79], how biological control is affected at a semi-field scale [80], and field-level deployments of biological control agents [81,82]. The combined use of an egg parasitoid (*Trichogramma deion* Riley (Hymenoptera: Trichogrammatidae)) and larval parasitoid (*Habrobracon hebetor*) reduced live *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) by 96% over simply bagging cornmeal in a simulated warehouse space, for example. At commercial food facilities, augmentative releases of *Theocolax elegans* 21 d after pest releases reduced insect fragments by 89–92% in bins with 27 tonnes of wheat compared to control bins without parasitoids [81]. Overall, for biological control of 19 stored product taxa evaluated by 13 natural enemies, 163 of 212 mortality estimates were between 70–100% [83].

Much research still needs to be conducted in this field in Canada. Only one study on the biological control of pests of stored products has been published from Canada, which was a screening of local *Trichogramma* species as candidates for the control of Indian-meal moth [84].

The commercialization of biocontrol agents against pests of stored products in North America sometime after 2002 and their discontinued commercialization and marketing sometime around 2015 indicates a failed attempt at adoption in the industry. Although a few companies marketed these biocontrol agents in North America during this time, they were sourced from a single producing supplier. Reliance on a single supplier was a weakness in the system and when this source discontinued production, the entire field caved in. Based on conversations with past vendors of these species it seems that an important issue was the lack of awareness and understanding of this technique by potential clients, so the market remained small, and no North American suppliers has taken over the production of these biocontrol agents.

6. Lessons Learned from Europe

Since the mid-1990s, the use of biological control to manage stored product infestations has been common in German speaking countries of Central Europe [2], Table 3. Most biocontrol applications target stored product moths in bakeries, food processing industries, retail trade and private households, as well as beetles in grain on farms [85]. A non-negligible portion (~$\frac{1}{4}$) of biocontrol applications target pests of museums, principally the common cloth moth *Tineola bisselliella* (Hummel) (Lepidoptera: Tineidae) [86,87]. Moths constitute half of the pest species targeted by commercial biocontrol in stored product environments in German speaking countries of Central Europe, and $\frac{3}{4}$ of the targets of field applications. The main targeted species are: *P. interpunctella*, *Ephestia kuehniella* Zeller, *E. elutella* (Hübner), and *Cadra cautella* (Walker) (Lepidoptera: Pyralidae). *Plodia interpunctella* alone is the target of over $^1/_3$ of field applications [85,86]. To target moth pests in homes, as well as in industrial bakeries and commercial facilities, the egg parasitoid *Trichogramma evanescens* Westwood (Hymenoptera: Trichogrammatidae) largely dominates the market with 60% of field applications [86]. To increase control efficacy, *T. evanescens* is often combined with the larval parasitoid *H. hebetor*. The former species is sold on cardboard plates with 3000 individuals (e.g., through MOTTENshop™, Natürliche Feinde GmbH, Vienna, Austria), while the latter is sold as adults or cocoons in cardboard boxes or plastic vials with 50 or 150 individuals (e.g., through Schneckenprofi, prime factory GmbH & Co. KG, Leipzig, Germany). The parasitoids will emerge from the cards over the course of 21 d at room temperature. Foundational research suggests that *T. evanescens* must be located adjacent to hosts [88], and thus, during deployment, one cardboard card should be placed on each shelf with stored products containing potential infestations. By contrast, *H. hebetor* will actively seek out infestations far from their release location, meaning one cardboard card is usually sufficient per moderately-sized contiguous room. Using this combination of species is generally lethal to moths because one species targets the eggs (e.g., *T. evanescens*), and the other targets larvae (e.g., *H. hebetor*). These programs have largely been successful at improving control of lepidopteran pests, while reducing complaints of insect contamination in baked goods facilities in Europe. Even more impressively, the stakeholders in German speaking countries of Central Europe appear to have readily accepted the use of natural enemies, including parasitoids, as a standard and culturally acceptable tactic for the management of stored product insects. This is true even for points relatively close to the consumer in the post-harvest supply chain such as industrial bakeries, where there is typically less tolerance for insect contamination of any sort. Most species of wasps used here are exceedingly small (0.5–2 mm), but larger species are also released, such as *Venturia canescens* (Gravenhorst) (Hymenoptera: Ichneumonidae) (5–7 mm long, ~10 mm with the ovipositor), which has been released in industrial bakeries in Germany for nearly a decade. None of these releases has ever led to a consumer complaint. Thus, it appears processors believe the wasps often will not be able to find their way into products, but if wasps do, they may escape unnoticed by consumers, or else be easily removed with other food dust and debris at facilities, and/or separated from grain by normal cleaning procedures. *Venturia canescens* frequently naturally occurs without complaints in bakeries in Central Europe and its common occurrence in these facilities may have helped its acceptance as a biocontrol agent.

Therefore, in light of the long and ongoing successful biological program for stored product facilities in Europe (not to mention other examples that have been beyond the scope of this contribution), and with successful laboratory, pilot-scale, and commercial demonstrations that biological control may work in the US, the pressing question is why has there been lingering reticence to adopt biological control in the US and Canada? This is even more perplexing considering the regulatory state-of-affairs in North America, where an exemption in tolerances in the US for beneficials has been carved out by the USEPA. It seems that biological control is much more of a taboo tactic among stakeholders at North American food facilities compared to European counterparts. For example, in North America, insects are probably most associated in the public's eye with filth and contamination, and there may be few facilities that want to be perceived by anyone, let alone consumers, as running operations "conducive" to the growth of insects, even if those insects are beneficial and for the protection of commodities. In addition, as noted above, there may be logistical constraints, including on supplies of natural enemies, as well as on information about their proper deployment. Thus, cultural perceptions that disincline stakeholders to biological control plus the lack of infrastructure to support supplying natural enemies for stored product insects, and dearth of translatable technical support may make it difficult for stakeholders to consider biological control a feasible alternative tactic in North America.

In Europe, the establishment of this practice has required time and efforts by its pioneers [85], particularly by informing people about the existence and benefits of biocontrol in stored products, including at workshops, at public events, demonstration of the efficacy of biocontrol agents at clients' locations, and reaching out to potential clients. These efforts were fruitful as they eventually led to the acceptance of the method and the development of networks of regular clients for vendors of biocontrol agents. Similar efforts probably will be necessary for firmly establishing the practice in North America. Furthermore, in Central Europe, many pest control operators are using natural enemies, and offer this option to potential clients in the food processing industry. Because there are often long-term relationships between pest control operators and their clients if North American pest control operators could offer biocontrol options it would significantly foster its widespread acceptance in North America.

7. Future of Biocontrol in North America

With hindsight, it is clear that there was an overreliance on a small handful of fumigants for too many decades in controlling stored product insects after harvest [89]. However, most fumigant options available to food facilities in the 1980s are no longer available today due to increasing regulatory restrictions, environmental, and worker safety concerns [12,90]. There has also been strong consumer demand for products with few or no insecticide inputs throughout the supply chain [37]. Finally, for the primary remaining fumigant (e.g., phosphine), there has been a dramatic worldwide increase in resistance by at least eight stored product taxa [91].

While many have hoped for a panacea as effective as the now-phased-out methyl bromide, after a considerable amount of time, effort, and creativity invested by researchers and stakeholders, it does not appear one is likely to arrive in the foreseeable future. As others have noted recently (e.g., [92]), it will increasingly be important to view food facilities as whole systems and to tailor integrated pest management (IPM) programs to the specific context, taking into account key biotic and cultural components of the system. Instead of looking to one solution, multiple tactics should be employed as appropriate for a facility in a layered approach with the sum total effect of all tactics reducing pest infestation below specified tolerances for damage.

In this paradigm, biological control may be viewed as an additional tactic to deploy in managing stored product insects at food facilities, but it is one that comes with significant advantages. For example, it can be used in conjunction with other methods [2]. Additionally, because it does not require insecticides, there is likely to be greater consumer acceptance, and may be able to provide an additional option for organic management of post-harvest commodities at a point in time when there are still scant options for organic food facilities. Despite certain regulations limiting the number of insect fragments in grain and processed products, including beneficial agents, we should keep in mind that these do not preclude the use of biocontrol agents in grain bins since it has been shown that the use of a parasitoids in wheat bins can considerably decrease overall insect fragments [81], and because the parasitoids and predators that attack stored product pests are typically very small they are easily removed from bulk grain before milling using normal cleaning procedures (e.g., elevator vacuum systems). Abiotic conditions (e.g., warmer temperatures, lack of moisture) help promote natural enemies, with storage structures often preventing emigration of beneficial organisms. This ensures that where hosts are present in structures, natural enemies will follow, often mediated by chemotaxis (e.g., [93,94]).

There are a few disadvantages to the use of biological control at food facilities as well. For these facilities, the main issue with stored product insects is their presence in the facility itself rather than in the products, so biocontrol agents should remain outside products, where the pests are. As we note above, parasitoids have been regularly released in industrial bakeries in Europe for over 20 years [8,85,95], and have never led to a consumer complaint. For these facilities there is more upfront education of stakeholders in properly deploying natural enemies, and important points to consider are (1) which natural enemies to deploy, (2) when to deploy natural enemies, (3) how frequently to release them, and (4) what sort of lag to expect between deployment and control. As a result, the use of biological control is a more knowledge-heavy endeavor, which may be another source of reluctance in this tactic in North America. Finally, it may be difficult to find suppliers for key natural enemies important for control of stored product insects in North America and obtaining permits for importing natural enemies internationally may be too confusing or not worth the time of managers at food facilities.

Thus, in moving forward with developing robust biological control programs for food facilities in North America, we conclude the following must be a priority. A stakeholder-centric view of biological control must be taken that prioritizes ensuring natural enemies are (1) easy and convenient to purchase and (2) easily deployed with a minimum of effort and knowledge. This will require that biological control be implemented in a modular, mobile, and easy-to-understand fashion (e.g., [96–98]). In addition, in supporting shifts in perceptions among stakeholders, it will be important to increase awareness of this field to generate a broad knowledge and acceptance, by prioritizing forming partnerships with Europeans researching stored product biological control to leverage connections and provide proof-of-concepts at European food facilities suitable to convincing North American stakeholders, while leveraging clear demonstrations of success with biological control at North American food facilities that are willing to be early adopters in key grain-producing regions.

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