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Review

Enhancing Food Grains Storage Systems through Insect Pest Detection and Control Measures for Maize and Beans: Ensuring Food Security Post-COVID-19 Tanzania

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Abstract: COVID-19 poses a significant threat to the present and future of mankind. The emergence of diverse strains during the pandemic creates uncertainty regarding their disappearance or resurgence. Lockdown measures and travel restrictions impact national and household food systems, hindering the movement of people and goods. Effective COVID-19 control requires science-based preventive measures and consideration of food availability. In Tanzania, resource-constrained farmers rely on the self-storage of food crops. Precise pest control information and tailored detection/storage systems are essential for preserving major staple foods such as maize and beans, which face frequent infestation by beetles and moths. Traditional methods used before the pandemic are insufficient compared to advanced global alternatives. This paper reviewed about 175 publications from different databases, dated from 1984 to 2023 (2023 to 2014 = 134, 2013 to 2004 = 26 and 2003 to 1984 = 15), assessing storage management for maize and beans. Identifying gaps between Tanzania and global advancements aiming to empower farming communities with the latest technologies and ensuring food security amid the pandemic.

Keywords: cereals; legumes; stored-insects; management; pandemic

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1. Introduction

Cereals and legumes play a crucial role in ensuring food availability, particularly in developing nations like Eastern Africa [1,2]. Legumes, in particular, are valuable sources of proteins, vitamins, minerals, and dietary fibres [3,4]. The global and Tanzania legume consumption is estimated at 6.5 and 16.2 kg/capita/year, respectively (Figure 1). In the regions of East and Southern Africa, *Phaseolus vulgaris*, commonly known as beans, holds significant importance both as a food crop and a cash crop [5]. It is worth noting that more than 34% of rural smallholder farmers cultivate beans, with a substantial portion, ranging from 16% to 41%, being sold for income generation.

Maize (*Zea mays* L.), on the other hand, holds significant importance in Sub-Saharan Africa, serving as a staple food, animal feed, source of income, and raw material for various industries [6,7]. Globally, maize is consumed at an estimate of 45.1 kg/capita/year while about 46.8 kg/capita/year is consumed in Tanzania (Figure 2). In Tanzania alone, over 7.4 million farmers are engaged in maize cultivation [8,9]. The global concerns of food security, hunger, and increasing poverty levels, especially in developing nations, highlight the pressing need for effective agricultural strategies [10]. While much emphasis has been placed on crop production, it is crucial to address the significant postharvest losses experienced in developing countries [11].

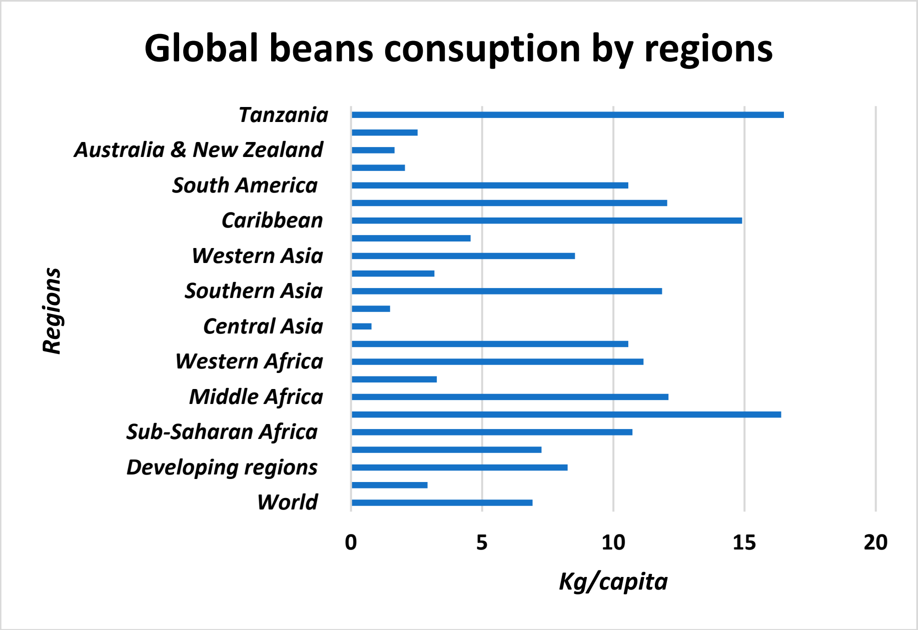

Figure 1. Worldwide and Tanzania beans consumption by regions (FAO Stat 2021).

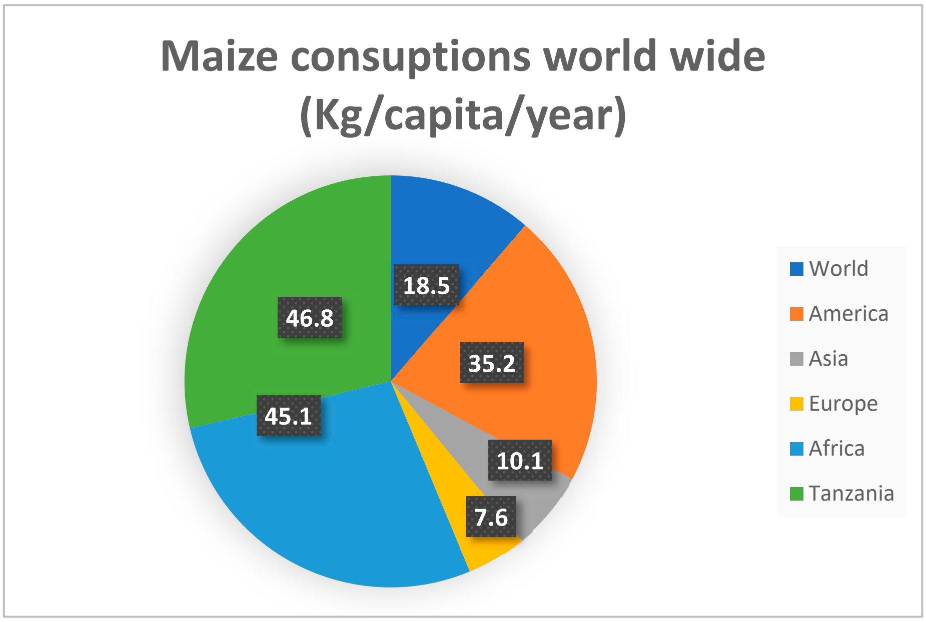

Figure 2. Worldwide and Tanzania maize consumption (FAO Stat 2021).

Postharvest loss is predominantly caused by insect pests ranging from 30–40% in cereals and 30–73% in legumes [5,12,13]. Notably, the major pests responsible for these losses include *Sitophilus zeamais* Motschulsky, 1855 (*Coleoptera*: *Curculionidea*): *Prostephanus truncatus* (Horn) (*Coleoptera*: *Bostrichidae*), and *Rhyzopertha dominica* (Fabricius, 1792) for maize, and *Callosobruchus maculatus* (Fabricius, 1775) for legumes [14]. Addressing these pest infestations is crucial to mitigate the significant losses encountered during the post-harvest stage.

In addition to the Ukraine war and global climate change, the world is currently under threat from SARS-CoV-2 (COVID-19), a disease that has profound implications for the health, education, and socioeconomic conditions of agricultural communities [15]. The implementation of lockdowns, social restrictions, and travel bans poses a significant risk to global food supply chains [16,17]. Policies aimed at preventing the spread of the disease also impact food production strategies [15,18]. Food security, which is as crucial as public health, hinges on the availability of staple foods within communities affected by social restrictions aimed at combating the virus [15]. Insufficient measures to prevent COVID-19 impede agricultural production and distribution. The global disparity in food availability and pricing further exacerbates food scarcity, particularly in rural areas [10]. The economic impact of the disease during the COVID-19 pandemic has resulted in widespread starvation [19]. This was greatly contributed by the rise of food prices [20]. It is essential to establish effective storage and protection systems for food products during times of crisis, such as the ongoing global pandemic [21].

This review of various databases (Figures 3 and 4) aims to examine the global advancements in maize and bean storage systems, recent methods of storage insect pest detection, and pest management while identifying gaps within the Tanzanian context. In so doing, the review will contribute to SDG 2, which emphasizes ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture. This information will assist rural communities in acquiring knowledge on how to store their own staple foods during crisis situations (Figure 5).

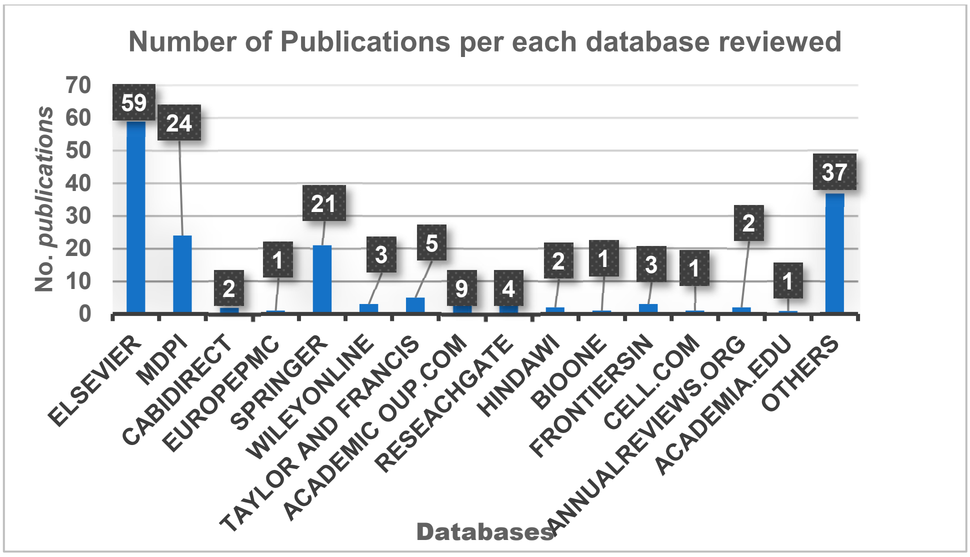

Figure 3. Number of publications reviewed per database.

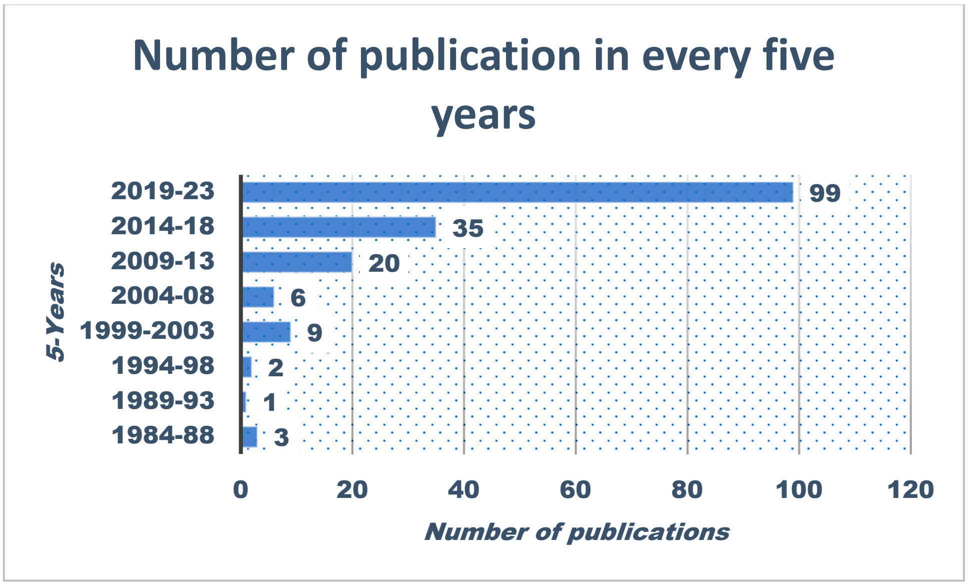

Figure 4. Number of publications reviewed every five years from 1984 to 2023.

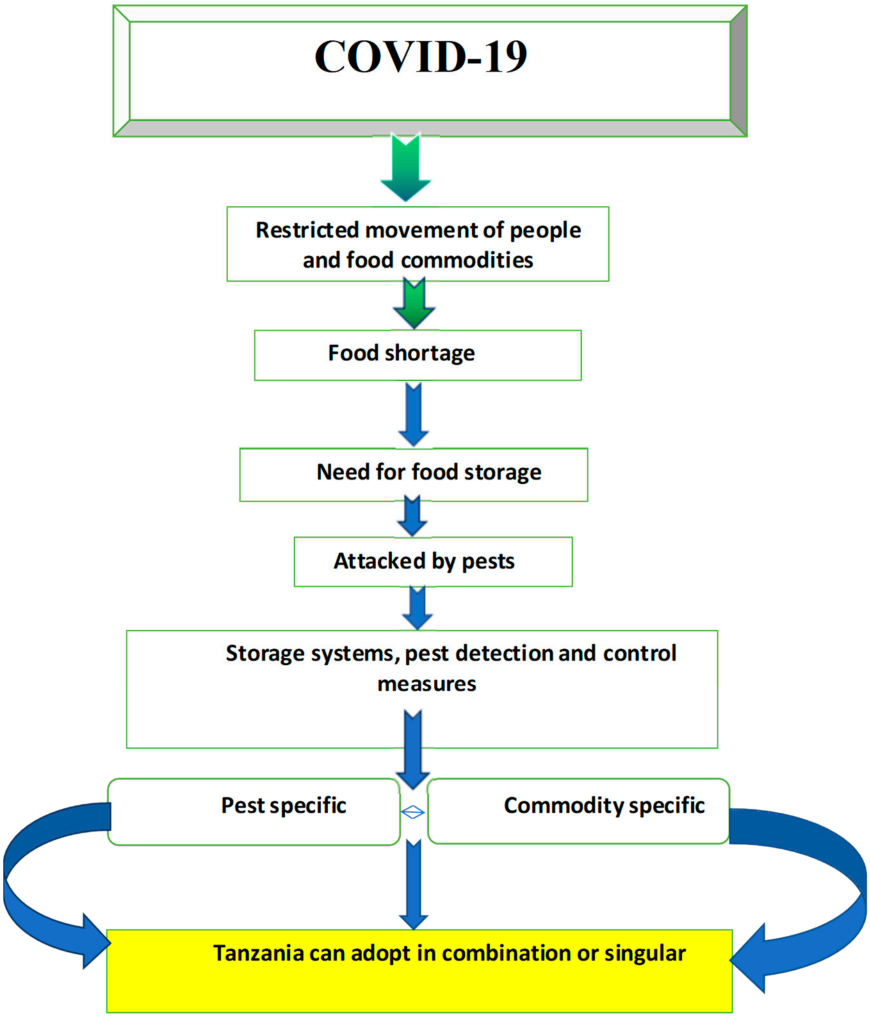

Figure 5. Systematic framework of storage pest and commodity specific advanced food storage measures to ensure food availability post COVID-19 crisis.

2. Common Storage Insect Pests of Maize

A multitude of insect species worldwide can inflict damage on maize grains, with the majority belonging to the coleopteran and lepidopteran groups [22]. Among these species are rice weevils (*Sitophilus oryzae* (L.) (*Coleoptera*: *Curculionidae*)), lesser grain borers (*Rhyzopertha dominica* (F.) (*Coleoptera*: *Bostrichidae*)), large grain borers (*Prostephanus truncatus* (Horn) (*Coleoptera*; *Bostrichidae*)), maize weevils (*Sitophilus zeamais* Motschulsky (*Coleoptera*: *Curculionidae*)), khapra beetles (*Trogoderma granarium* Everts (*Insecta*: *Coleoptera*: *Dermestidae*), red flour beetles (*Tribolium castaneum* (Herbst) (*Coleoptera*: *Tenebrionidae*), granary weevils (*Sitophilus granarius* (L.) (*Coleoptera*: *Curculionidae*), cigarette beetles (*Lasioderma serricorne* (F.) (*Coleoptera*: *Anobiidae*), drugstore beetles (*Stegobium paniceum* (Linnaeus, 1758) (*Coleoptera*: *Ptinidae*), Angoumois grain moths (*Sitotroga cerealella* (Olivier) (*Lepidoptera*: *Gelechiidae*), rice moths (*Corcyra cephalonica* (Stainton) (*Lepidoptera*: *Pyralidae*), sawtoothed grain beetles (*Oryzaephilus surinamensis* (L.) (*Coleoptera*: *Silvanidae*), long-headed flour beetles (*Latheticus oryzae* Waterhouse (*Coleoptera*, *Tenebrionidae*), confused flour beetles (*Tribolium confusum* Jacquelin Du Val (*Coleoptera Tenebrionidae*), large flour beetles (*Tribolium destructor* Uyttenboogaart (*Coleoptera*: *Tenebrionidae*), Indian meal moths (*Plodia interpunctella* (Hubner 1857) (*Lepidoptera*: *Pyralidae*), yellow mealworms (*Tenebrio molitor* (Linnaeus) (*Coleoptera*: *Tenebrionidae*), flat grain beetles (*Cryptolestes pusillus* (Schönherr) (*Coleoptera*: *Laemophloeidae*), and almond moths (*Cadra cautella* (Walker) (*Lepidoptera*: *Pyralidae*). In East Africa, *P. truncatus* and *S. zeamais* are the most destructive species [23]. Both species, *P. truncatus* and *S. zeamais*, are pre and post-harvest primary coleopteran pests of maize inflicting grain loss between

5% and 45% during storage [24]. If left unchecked, these storage pests can cause substantial losses in both the quality and quantity of maize grains [25].

3. Common Storage Insect Pests of Beans

The most significant insect pests that affect bean storage include Chinese bruchid (Linnaeus, 1758) (*Callosobruchus chinensis*) (*Coleoptera*: *Chrysomelidae*), Pulse beetle (*Callosobruchus maculatus*) (Fabricius 1775) (*Coleoptera*: *Bruchidae*), Bean weevil (*Callosobruchus analis* (Fabricius, 1781) (*Coleoptera*: *Bruchidae*), Bean weevil (*Acanthoscelides obtectus* (Say, 1831) (*Coleoptera*: *Bruchidae*), Mexican Bean Weevil (*Zabrotes subfasciatus*) (Bohemann, 1833) (*Coleoptera*, *Chrysomelidae*, *Bruchinae*), *Bruchidius incarnatus* (Boheman, 1833) (*Coleoptera*: *Bruchidae*), Broadbean seed beetle (*Bruchus rufimanus* (Boheman, 1833); *Coleoptera*: *Chrysomelidae*), *Bruchus dentipes* (Baudi 1886) (*Coleoptera*: *Bruchidae*), *Bruchidius quinqueguttatus* (Olivier, 1795) (*Coleoptera*: *Chrysomelidae*), *Bruchus emarginatus* (Allard, 1868) (*Coleoptera*: *Chrysomelidae*), *Bruchus ervi* (Frölich, 1799) (*Coleoptera*: *Chrysomelidae*, *Bruchus lentis* (Frölich, 1799) (*Coleoptera*: *Chrysomelidae*, and *Bruchus pisorum* (Linnaeus, 1758) *Coleoptera*: *Chrysomelidae* [5,26,27]. Among these pests, *C. chinensis* is particularly damaging and can cause losses of up to 50% in beans, peas, and lentils [12].

4. Cereals and Legumes Storage Systems

On-farm storage systems are widely employed in many developing countries and play a crucial role in ensuring continuous food availability throughout the year [28]. These systems encompass various structures and techniques, such as fireplaces, cribs, roofs, woven granaries, mesh or net structures, bins, underground pits, and wooden platforms [29,30]. Such storage methods are particularly suitable for maize grains that have been stored intact with the ear corn. In Asia and Mexico, maize is often stored on elevated rafters to reduce moisture content and deter insect infestations [31]. Wrapping bamboo and wooden poles with wire mesh or steel netting is another common practice for storage bins in China and Central America [32]. Woven granaries made from bamboo and straws are also widely used in Asia, Africa, and Latin America [29].

Dunkel [33] provides a description of underground grain storage pits coated with straw or woven bamboo. In India, traditional grain storage structures such as Kanaja (mud and cow dung smeared bamboo structure), kothi (built store), sanduka (wooden boxes for cereals and legumes), utrani (burnt clay pots), and hagevu (underground pit of stones or straws) are widely utilized [34]. In order to enhance grain storage conditions, mud clay pots coated with cement or bitumen are also employed [28]. Additionally, in Nepal, bins made of mud sandwiched between polyethylenes are utilized [28]. However, these storage structures have the drawback of occupying space even when empty.

Polypropylene synthetic bags and sisal sacks are widely employed and highly beneficial to farming communities. These bags offer portability for both storage and transportation purposes, occupying minimal space when filled with grain as well as when empty [30]. Their versatility and convenience make them valuable tools in agricultural storage practices.

Non-hermetic storage systems, such as self-built household silos, community storage buildings, and warehouses, are commonly found in many developing countries. These storage facilities can be complemented with various pesticides to eliminate any existing insect pests. However, non-hermetic storage solutions lack an airtight barrier, making them ineffective in eradicating insects already present in the grains [35]. Although these storage systems offer protection against theft, their inability to create an air barrier limits their efficacy in pest control.

Hermetic storage systems are designed to modify the atmospheric conditions within airtight silos or bags, reducing oxygen levels and increasing CO_2 concentrations to inhibit the respiration of storage insects [36]. These systems have been proven effective in preserving the quality and quantity of various grains, including maize [37], cowpea [38], and rice [39], across different agroecological settings. Airtight bags, among the available storage solutions, are both technically and economically feasible for farmers [40]. These hermetic bags typically consist of polyethylene bags (80-micron thickness) layered between polypropylene or traditional bags with capacities ranging from 25 kg to 100 kg [41]. While metal silos are a more expensive option due to the cost of galvanized iron sheets, labor, and transportation [42,43]. Hermetic bags are susceptible to punctures caused by sharp objects, grains, and rodent damage during transport or storage. Another alternative is the silo-bag, a tube-like structure made of a plastic bag capable of storing approximately 200 metric tonnes of maize, wheat, or soybean [44]. In addition, other forms of hermetic metal silos include cocoons which are widely used in Rwanda, Ghana, and the Philippines for storage of shelled and unshelled maize. This type is modified to absorb gases against the deformation of the storage system [45].

In Tanzania, traditional storage options such as open barrels, jute or polypropylene sacks/bags, and Vihenge bins were commonly used before and during the COVID-19 pandemic [1,46]. The duration of grain storage typically ranged from three months to a year, depending on factors like crop quantity, storage capacity, and farmer preferences [1]. However, new storage technologies like Zerofly bags [47] and airtight bags [48] have emerged in some regions of East Africa. Although these technologies provide effective protection against storage pests, the knowledge and skills of farmers in their proper usage vary significantly across farming communities in the region. Additionally, many sellers promote and market these new technologies without considering the need for farmer training on the correct application. The current understanding and adoption of these advanced technologies, as well as their appropriate implementation in Tanzania, remain inadequately explored.

5. Storage Pest Detection Methods

Accurate and timely pest detection in storage facilities is crucial for effective pest control. The advancements in pest detection technologies globally have encompassed a range of tools and techniques, from simple to sophisticated. However, there is a notable knowledge gap in storage pest detection methods specific to East Africa. In Tanzania for example, prior to the COVID-19 pandemic, pest infestations in storage were primarily identified through sensory evaluation, such as smell and visual inspection of maize for signs of decay, along with long-term temperature monitoring in the storage containers [49]. Recently, [50] studied acoustic, pitfall trap, and visual surveys of stored product insect pests in Kenya and found them to be useful detection methods. Despite the usefulness smell and visual inspection are time-consuming and susceptible to grain losses. Acoustic methods have been developed and are widely used on a global scale for detecting infestations of internally feeding insects. These methods include both expensive commercial devices [51] and low-cost electronic sound-sensing detection devices [52]. These innovative insect detection techniques offer automated pest detection systems for granaries and warehouses. Deep learning approaches, machine learning techniques, image processing techniques, and opto-acoustic techniques are among the methods mentioned in the literature [52].

Chen, et al. [53] conducted a study on an automatic pest detection system based on YOLOv4, a classic single-stage deep learning object detection model, and found it to be more than 95% accurate in detecting beetles and weevils in storage facilities. Another study by [54] demonstrated the effectiveness of improved YOLOv5 in detecting and identifying multiple pests in granaries. Nyabako, et al. [55] concluded that machine learning can be used to predict *P. truncatus* populations and associated grain damage.

Modern insect detection methods, such as soft X-ray detection, near-infrared spectroscopy, laser detection, and convolutional neural networks (CNNs), have also been shown to be effective in detecting storage pests [56–59]. Some authors have illustrated modern machine learning models that not only detect but also estimate insect populations in storage facilities for decision-making purposes. These models include Region-based Convolutional Neural Networks (R-CNN) [60], Fast Region-based Convolutional Neural Networks (Fast-RCNN) [60,61], Modified Dilated Residual Networks (MDRN) [62], RetinaNet [63], Single Shot MultiBox (SSD) [64], and U-net-like frequency-enhanced saliency (FESNet) [65]. An improved extended residual network detection using computer vision has also been proposed by [66]. However, Ref. [1] tested only a few of these methods in some East African countries, including Tanzania, despite their limited use by smallholder farmers in the country. While these novel insect detection techniques offer precision and timeliness, they are expensive and challenging to detect immature insects hidden within grains.

6. Management of Storage Insect Pests

In stores, insect pests can be effectively controlled using a range of methods including biological, chemical, botanical, and cultural approaches, as well as through host-plant resistance, irradiation, hermetic bags and silos, Zerofly bags, silicon dioxide, chlorine dioxide, ozone gas, radio frequencies, diatomaceous earth, Long-Lasting Insecticide-incorporated Netting (LLIN), and essential oils derived from various plants. These methods can be employed individually or in combination, depending on factors such as the complexity of the pest population, farmers' knowledge, and affordability. Before the incidence of COVID-19 farmers in Tanzania were only using synthetic pesticides such as organophosphate and synthetic pyrethroids, botanicals, hermetic bags, metal silos and diatomaceous earths [67]. The selection and application of these control techniques for combating storage insect pests usually vary considerably depending on the specific commodity and the farming community involved. Each method has its advantages and limitations, and their suitability is often influenced by factors such as the type of pest, local environmental conditions, available resources, and regulatory considerations. Therefore, an integrated approach that combines multiple strategies tailored to the specific circumstances is often recommended for effective and sustainable pest management in storage facilities.

6.1. Chemical Control

The effective control of storage insect pests in different commodities often requires the use of specific active ingredients, either individually or in combination. Ref. [68] extensively discussed the combined use of pirimiphos-methyl and permethrin or fenitrothion and fenvalerate to control the pest complex consisting of *P. truncatus*, *Sitophilus* sp., and *T. castaneum*. Gourgouta, et al. [69] found that a commercial cypermethrin formulation was effective against *S. oryzae*, *O. surinamensis*, *R. dominica*, and *P. truncatus* infesting wheat and maize. Various fumigants have also been employed for grain fumigation to combat storage pests. Phosphine, sulfuryl fluoride, ethyl formate, methyl bromide, carbonyl sulfide, propylene oxide, and allyl isothiocyanate have been used for this purpose. Phosphine and methyl bromide are commonly used and effective for large-scale fumigation of storage facilities [70,71]. In addition to fumigants, alternative control methods have been explored. Ozone gas (O_3) has demonstrated efficacy against phosphine-resistant strains of red flour beetles, saw-toothed grain beetles, maize weevils, and rice weevils [72,73]. Chlorine dioxide has shown effectiveness against red flour beetles, lesser grain borers, saw-toothed grain beetles, maize weevils, and rice weevils [74–76]. Ref. [77] also found that a combination of wood vinegar and the chemical insecticide deltamethrin was 90% effective against *Sitophilus oryzae*. It is important to note that the choice of control method and active ingredient depends on the target pest species, the type of commodity being protected, and factors such as safety, environmental impact, and regulatory considerations. Further research and evaluation are needed to determine the optimal combination and application techniques for efficient and sustainable pest management in storage facilities.

6.2. Botanicals

Botanicals contain active substances that are effective in fighting storage pests. In many plants, especially essential oils, they have insecticidal properties [78]. These plants are used for the purpose of keeping pests out of stored grains. In the past, dried or ground plants have been mixed with stored grains. [79] collected and examined 59 pesticidal herbs in Sub-Saharan African countries and found *Capsicum annuum* L., *Aloe vera Miller*, *Croton macrostachyus Hochst*, *Boswellia papyrifera*, *Kleinia* spp., *Vernonia amygdalina Del.*, *Euphorbia* spp., *and Carissa schimperi* to be effective against storage pests [79]. Farmers use them as insecticides in the form of plant extracts and powders to protect storage insect pests such as *Sitophilus oryzae*, *Sitophilus zeamais*, *Callosobruchus chinensis*, *C. maculates*, *Tribolium castaneum*, *Rhyzopertha dominica*, and *Trogoderma granarium Everts* [80].

According to the findings by [81], powders and essential oils (EOs) of *Artemisia absinthium* aerial parts, *Melia azedarach* fruits, *Trigonella foenum-graecum* seeds, and *Peganum harmala* seeds can fight adult *T. castaneum* in cereal grains. [82] discovered that neem seed, leaf powder, and garlic can lower rice weevil populations by more than 65%.

Essential oils (EOs) extracted from various plants have shown great potential as insecticides against storage insect pests, with diversified mechanisms of action and safety for mammals and non-target organisms [83]. These plant bioactives exhibit fumigant, contact toxicity, repellent, antifeedant, ovicidal, oviposition deterrent, and larvicidal activities. They can also interfere with neurotransmitters involved in nerve impulses, such as acetylcholine esterase (AChE), octopamine, and amino butyric acid (ABA). The extraction method of essential oils can influence their toxicity against stored insect pests. [84] found that ultrasound extraction of *Ocimum basilicum* resulted in toxicity against adult *Sitophilus zeamais*. Ref. [85] tested the toxicity of nanoencapsulated *Eucalyptus largiflorens* on the cowpea weevil, C. maculatus, and observed persistent and toxic. Mint and rosemary essential oils were found to affect the mating fitness of *C. maculatus* [86]. Ref. [87] discovered that lemongrass essential oil and citral had a significant antifeedant effect on *C. maculatus*. A comprehensive review on stored-product pest management [88], highlighted the efficacy of essential oils such as eucalyptol, camphor, linalool, eugenol, limonene, terpinen-4-ol, menthone, and anethole in terms of fumigation and contact toxicity. Ref. [89] investigated essential oil-based nanoemulsions of *Carlina acaulis* L., *Mentha longifolia* (L.) Huds., and *Hazomalania voyronii* (Jum.) and found them to be effective against *S. oryzae*. A review conducted by [90] revealed that EOs from 121 species and 26 families exhibit efficacy against *C. maculatus*. These EOs primarily consist of terpenoids and sesquiterpenoids, acting as fumigants, contact toxins, and repellents. Despite the effectiveness of EOs against storage pests, their practical application in Tanzania is still limited due to a lack of appropriate dosage, insufficient knowledge, and limited availability. Further research and exploration are needed to determine the optimal application methods and formulations for the utilization of EOs in storage pest management in Tanzania.

6.3. Long-Lasting Insecticide-Incorporated Netting (LLIN)

The use of LLIN technology, initially developed for controlling disease vectors in tropical regions, has recently been tested in agriculture [91]. While previous research has demonstrated the effectiveness of LLIN against storage beetles, it has also been utilized as an insect trap in crop plants and for managing nuisance pests in residential settings [92]. In a study by [93], the effects of LLIN were compared between immature and mature *T. castaneum* and *T. variabile*. The researchers found that the movement and dispersal abilities of the adult beetles were significantly reduced compared to the larvae when exposed to LLIN. This research highlights the potential of LLIN technology as a versatile tool for pest management, not only in storage environments but also in agricultural crops and residential settings. Further studies are needed to explore its efficacy against various pests and optimize its application strategies in different contexts.

6.4. Insects Growth Regulator (IGR)

Methoprene and pyriproxyfen are insect growth regulators (IGRs) commonly used in agricultural systems for pest control [94]. These IGRs have been tested in combination with deltamethrin and cyfluthrin against storage pests, with a particular focus on immature insects [95]. IGRs are typically insecticides that target insect juvenile hormones (JH) and can include hormone analogues [96]. Their mode of action involves affecting the growth, development, metamorphosis, and chitin synthesis of immature insects [97]. The different modes of action of IGRs are classified as juvenile hormone agonists, ecdysteroid agonists, and chitin synthesis inhibitors [98]. These insect growth regulators have a significant impact on insect growth, reproduction, and behavior [99]. Studies by [94] have shown the effectiveness of methoprene against pests such as *R. dominica*, *T. castaneum*, and *S. cerealella* in maize, paddy, and wheat. Methoprene has also demonstrated efficacy against *P. interpunctella*, *T. castaneum*, *C. ferrugineus*, and *R. dominica*, leading to a disruption in the development (metamorphosis) of immature insects and a subsequent reduction in insect populations on infested commodities [100,101]. Overall, IGRs, particularly methoprene, have shown promise in controlling storage pests by targeting their growth, development, and reproduction, leading to effective population reduction. Further research is needed to explore their application in different pest management strategies and agricultural contexts.

6.5. Cultural Control

The implementation of certain measures and changes in storage environments and practices can significantly reduce the likelihood of infestation by primary storage pests such as *S. zeamais* and *P. truncatus*. These methods include removing residues from the previous harvest and regularly adjusting the ambient temperature [102,103]. Increasing the airflow rate during aeration has been found to have a greater impact on reducing populations of adult *Sitophilus* spp. and *R. dominica* [104]. Ref. [105] demonstrated that controlling *S. granaries* and *C. chinensis* can be achieved by using hypoxic nitrogen at concentrations ranging from 99% to 100% in silos. The resistance of host plants to storage pests is influenced by biochemical and physical characteristics, such as high phenolic concentrations [106]. Ref. [107] investigated the susceptibility of different maize genotypes to the larger grain borer and found that protein content is an important trait determining maize grain susceptibility to this pest. Loneliness has been shown to affect the life expectancy of male and female *Callosobruchus* spp. [86]. Additionally, periodic disturbance of maize grains and beans can effectively suppress populations of storage pests such as *S. zeamais* and *A. obtectus* by more than 90% [108]. By implementing these measures and understanding the factors influencing susceptibility in host plants and changes in storage environments, it is possible to mitigate the infestation of primary storage pests and enhance pest management strategies in storage facilities.

6.6. Biological Control

Teretrius nigrescens, a predator, has been proven to be highly beneficial in controlling *P. truncatus* populations in various countries, including Togo, Kenya, Benin, Ghana, Tanzania, and Malawi [109]. In the case of *S. zeamais*, several studies have been conducted to identify potential bio-control agents, with one standout candidate being *Theocolax elegans*, a small wasp (1–2 mm) that targets primary grain pests such as *Sitophilus* spp., *R. dominica*, *S. paniceum*, *Callosobruchus* spp., and *S. cerealella* [110]. Interactions between *Beauveria bassiana* and *Isaria fumosorosea* were found to be more than 66% effective against weevils, specifically *Sitophilus* spp. [111]. Recent research by [112] demonstrated that *M. anisopliae* and *I. fumosorosea* are highly effective against *S. granarius* and *S. oryzae*, resulting in 84–90% mortality rates. Ref. [113] reported that *M. anisopliae* and *Diatomaceous earth* (DE) exhibited remarkable efficacy, causing more than 95% mortality in insects such as *R. dominica*, *S. oryzae*, and *T. confusum*. These studies highlight the potential of bio-control agents and entomopathogenic fungi in the management of storage pests. By harnessing the predatory abilities of insects like *T. nigrescens*, the parasitic nature of wasps such as *Theocolax elegans*, and the effectiveness of entomopathogenic fungi like *Beauveria bassiana* and *Metarhizium anisopliae*, it is possible to develop environmentally friendly and sustainable approaches for pest control in grain storage facilities.

6.7. Hermetic Storage

Hermetic storage technology is a method that involves creating a sealed storage environment where carbon dioxide (CO_2) accumulates, and oxygen levels are depleted, creating an inhospitable condition for the survival of insects and fungi [45,114,115]. In a sealed storage condition for maize grains, insects and fungi consume the available oxygen, leading to unfavorable conditions for their survival [48]. An on-farm trial conducted by Likhayo, et al. [116] in Naivasha and Nakuru, Kenya, demonstrated the efficacy of hermetic storage. They observed that weight losses of maize grains were only 1.5% and 1.8% in metal silos and super Grain IV-R bags, respectively, compared to a substantial 32% in polypropylene bags after 270 days of storage. This finding highlights the high efficacy of hermetic storage in preserving grain quality. Ref. [117] tested the effectiveness of Purdue Improved Crop Storage (PICS) bags in Benin, Ghana, and Burkina Faso. They found that PICS bags achieved 95–100% mortality of adult *P. truncatus* and *S. zeamais*, indicating their efficacy in controlling these pests. In the study by [47], Zerofly bags were evaluated for their effectiveness against *S. oryzae*, *T. castaneum*, and *R. dominica*. The results showed that these bags provided a 99% mortality rate in less than three hours, demonstrating their ability to protect maize grains from storage insect pests. Furthermore, Deltamethrin-infused Zerofly bags were found to be highly effective in controlling stored insect pests. Ref. [6] evaluated different hermetic bag storage methods and found that Zerofly hermetic bags, PICS bags, and non-hermetic Zerofly bags were highly effective in controlling insects and aflatoxin in maize grains. A study conducted by [118] investigated the efficacy of PICS bags and metal silos over a seven-month storage period. The results showed that both PICS bags and metal silos were highly effective in controlling the storage of insect pests. Collectively, these studies demonstrate the effectiveness of hermetic storage technologies, such as PICS bags, Zerofly bags, and metal silos, in controlling the storage of insect pests and preserving grain quality over extended periods of storage. These methods provide valuable options for farmers to mitigate post-harvest losses and ensure food security.

6.8. Inert Substances

Inert substances, such as diatomaceous earth (DE), amorphous silicon dioxide, and diamond dust, have been observed to cause cuticular abrasion and absorb lipids in insect cuticles [119]. Ref. [120] conducted a study investigating the synergistic effects of Spinosad, diatomaceous earth, and *Trichoderma harzianum* against *S. oryzae*. The combination was found to be effective in controlling the insect population. In a similarly designed study, Saeed, Wakil, Farooq, Shakeel, Arain and Shakeel [119] demonstrated the effectiveness of combining *M. anisopliae* and diatomaceous earth (specifically Grain-Guard) against *Latheticus paeta*, *C. ferrugineus*, *R. dominica*, and *T. castaneum*. Agrafioti [121] conducted research on silicon dioxide (SiO_2) coated insect-proof nets and their effectiveness against *S. oryzae*. The study found a 100% reduction in the insect population after seven days of exposure to the nets. Ref. [122] tested several inert substances and found them to be effective against khapra beetle (*T. granarium*). Fields [123] found that pea-protein-treated grains resulted in a few *C. ferrugineus*, *S. oryzae*, *S. zeamais*, *T. castaneum*, *and T. confusum*. The majority of these substances showed advantageous effects in reducing the *T. granarium* population. The use of inert substances, such as diatomaceous earth, amorphous silicon dioxide, and diamond dust, either alone or in combination with other control agents, has been shown to be effective in controlling various storage insect pests. These findings contribute to the development of alternative and environmentally friendly approaches for pest management in storage systems.

6.9. Mass Trapping

Pheromones can be utilized for monitoring and controlling stored-product insects [124]. Savoldelli and Trematerra [125], review indicated pheromones to be a promising tool for monitoring and control through mass-trapping and mating-disruption of stored-product insect pests. Food oils have been utilized as kairomones to attract adult *T. castaneum* beetles. The pheromones, specifically 4,8-dimethyldecanal, and the kairomone properties of food oils have been found to significantly impact the trapping of *T. castaneum* adults and the emergence of their progeny, providing valuable insights into the chemical ecology and behavior of these storage pests [126]. Fargo [127] showed that differences in insect species, grain temperatures, and trapping duration can affect trap catches during the estimation of insect abundance in stores.

6.10. Ionizing Radiation

Ionizing radiation is a well-established method employed for sterilizing, eradicating, or preventing the emergence of insect pests in food products. By inducing oxidative stress and causing DNA damage, ionizing radiation effectively eliminates infestations. Various sources of ionizing radiation, such as gamma rays from cobalt-60 and cesium-137, high-energy electrons, X-rays, and UV radiation, are commonly utilized for this purpose in the food industry [128]. In the case of *P. interpunctella*, [129] discovered that neutron irradiation proved to be an effective means of control. Another promising approach is radiofrequency heating, as demonstrated by [130], which allows for pest control through the application of heat without leaving behind chemical residues. While many management options have been extensively researched and implemented against storage pests in sub-Saharan Africa and other regions, their application in Tanzania remains limited, highlighting the need to bridge this gap in knowledge and practice.

7. Conclusions and Prospect

Finally, this review emphasizes the importance of improving storage practices for staple foods in developing countries like Tanzania, particularly in light of the COVID-19 pandemic and the need to ensure food availability for smallholder farming communities. The grain storage systems, pest detection techniques, and control practices for maize and beans, which are the main staple foods in Tanzania, are summarized. The review highlights that traditional methods were predominantly used for pest detection and control in Tanzania before and during COVID-19, while more advanced techniques and technologies are available globally.

The document underscores the need for an agricultural extension system in Tanzania to address the gap in pest detection and control measures in storage facilities, drawing from the global outlook and adopting modern approaches. It also suggests that control measures effective against one pest can be tested and applied to closely related pests, as seen in other regions. This information provides valuable guidance for developing comprehensive storage insect control strategies targeting stored maize and beans in Tanzania.

By implementing these measures, Tanzania can enhance its food security and ensure a steady food supply beyond the COVID-19 pandemic. The tabulated information (Table 1) presented in this review serves as a valuable resource, broadening the range of options for grain storage pest control measures and aiding in the development of effective and sustainable pest management packages for stored maize and beans in the country.

Table 1. Summary of storage pest management strategies, crops, mode of action, and their respective insect pests.

Method	Product Common Names	Insect Pest	Insect Stage	Mode of Action	Crops	References
Chemical	Deltamethrin, Pirimiphos-methyl + permethrin, fenitrothion + fenvalerate,	*P. truncatus*, *Sitophilus* sp. and *Tribolium castaneum*	Larval and adult	Toxicity	Maize	[68]
	Cypermethrin	*Sitophilus oryzae* (L.), *Oryzaephilus surinamensis* (L.), *Rhyzopertha dominica* (F.) and *Prostephanus truncates*	Larval and adult	Toxicity	Maize	[69]

Table 1. *Cont.*

Method	Product Common Names	Insect Pest	Insect Stage	Mode of Action	Crops	References
	Fumigants (phosphine, sulfuryl fluoride, ethyl formate, methyl bromide, carbonyl sulfide, propylene oxide and allyl isothiocyanate).	All storage insect pests	Egg, Larval, Pupa and adult	Toxicity	Maize and Beans	[70]
	Ozone gas (O_3)	*Tribolium castaneum*, *Oryzaephilus surinamensis* *Sitophilus zeamais*, *Rhyzopertha dominica* and *Sitophilus oryzae*	Egg, Larval, Pupa and adult	Toxicity	Maize	[131,132]
	Chlorine dioxide	*Tribolium castaneum*, *Rhyzopertha dominica*, *Oryzaephilus surinamensis*, *Sitophilus zeamais* and *Sitophilus oryzae.*	Adult and Larva	Toxicity	Maize	[133]
Botanicals	*Mentha piperita*, *Pinus roxburghii* and *Rosa* spp.	*S. zeamais* and *S. oryzae*	Larva and Adult		Maize	[134,135]
	Cymbopogon citratus	*Sitophilus granarius*	Adult	Toxicity	Maize	[136,137]
	Rosmarinus officinalis and *Zataria multiflora*	*Tribolium confusum.*	Adult	Toxicity	Maize	[138]
	Citrus sinensis peel	*Sitophilus zeamais*	Adult	Toxicity	Maize	[139]
	Thymus vulgaris	*Acanthoscelides obtectus*	Adult	Toxicity, Oviposition deterrent and Oxidative	Beans	[140]
	Cannabis sativa	*Cryptolestes ferrugineus*, *Rhyzopertha dominica*, *Sitophilus oryzae*, *Cryptolestes turcicus*, *Tribolium confusum* and *Stegobium paniceum*	Adult	Toxicity	Maize	[141]
	Artemisia sieberi	*S. oryzae*, *T. castaneum* and *R. dominica*	Larva and adult	Toxicity	Maize	[83,142]
	Gomortega keule and *Laurelia sempervirens*	*A. obtectus*	Larva	Toxicity	Beans	[83]
	Rosmarinus officinalis	*S. oryzae* and *O. surinamensis*	Larva and adult	Toxicity	Maize	[143]
	Eucalyptus lehmannii and *E. astringens*	*T. Castaneum* and *R. dominica*	Larva and adult	Toxicity	Maize	[83]
	Hyssopus officinalis, *Origanum majorana* and *Thymus zygis*	*S. oryzae*	Larva and adult	Toxicity	Maize	[144]
	Boswellia carterii	*C. chinensis* and *C. maculatus*	Larva and adult	Toxicity	Beans	[145]
	Lippia javonica	*S. zeamais*	Larva and adult	Toxicity	Maize	[146]
	Evodia lenticellata	*T. castaneum*, *L. serricorne* and *L. bostrychophila*	Larva and adult	Toxicity	Maize	[147]
	Cinnamomum zeylanicum and *Syzygium aromaticum*	*S. granarius*	Larva and adult	Toxicity	Maize	[136]
	Melissa officinalis	*T. castaneum*	Larva and adult	Toxicity	Maize	[148]
	Ostericum viridiflorum	*T. castaneum*	Larva and adult	Toxicity	Maize	[149]

Table 1. *Cont.*

Method	Product Common Names	Insect Pest	Insect Stage	Mode of Action	Crops	References
	Mentha piperita	*T. castaneum*, *L. serricorne* and *L. bostrychophila*	Larva and adult	Toxicity	Maize	[150]
	Lippia origanoides, *Tagetes lucida*, *Rosmarinus officinalis*, *Cananga odorata*, *Eucalyptus citriodora* and *Cymbopogon citratus*	*S. zeamais*	Larva and adult	Toxicity	Maize	[151]
	Zanthoxylum Xanthoxyloides	*A. obtectus*	Larva and adult	Toxicity	Beans	[152]
	Atalantia monophylla and	*S. oryzae*,	Larva and adult	Toxicity	Maize	[153]
	Citrus sinensis	*R. dominica* and *L. serricorne*	Larva and adult	Toxicity	Maize	[154]
	Asarum heterotropoides	*L. serricorne* and *L. bostrychophila*	Larva and adult	Toxicity	Maize	[155]
	Artemisia brachyloba	*T. castaneum*	Larva and adult	Toxicity	Maize	[156]
	Evodia rutaecarpa	*S. oryzae* and *T. castaneum*	Larva and adult	Toxicity	Maize	[157]
	Tagetus terniflora, *Cymbopogon citratus* and *Elionurus muticus*	*S. oryzae*	Larva and adult	Toxicity	Maize	[83]
	Gaultheria procumbens	*S. oryzae* and *R. dominica*	Larva and adult	Toxicity	Maize	[143]
	Pimpinella anisum, *Cuminum cyminum*, *Eucalyptus camaldulensis*, *Origanum syriacum* and *Rosmarinus officinalis.*	*T. confusum*	eggs	Toxicity	Maize	[158]
	Anethum sowa	*C. maculatus*	Adults	Oviposition deterrency	Beans	[159]
	Lavandula hybrida, *Rosmarinus officinalis* and *Eucalyptus globulus.*	*A. obtectus*	Adults	Oviposition deterrency	Beans	[160]
	Lippia alba and *Callistemon lanceolatus*	*C. lanceolatus* *C. chinensis*	Adult	Oviposition deterrency	Beans	[161]
	Mentha spicata	*C. chinensis*	Adults	Oviposition deterrency	Beans	[162]
	Acorus calamus	*C. chinensis*	Adults	Ovicidal	Beans	[163]
	Boswellia carterii	*C. chinensis* and *C. maculatus*	Eggs, larva and adult.	Larvicidal, Ovicidal and Oviposition deterrents	Beans	[145]
	Atalantia monophylla	*C. maculatus*	Eggs	Ovicidal activity	Beans	[153]
	Vanillosmopsis arborea	*C. maculatus*	Adults	Oviposition deterrency	Beans	[164]
	Lippia sp., *L. somulensis*, *L. grandifolia*, *L. wilmsii*, *L. dauensis* and *L. javanica.*	*S. zeamais*	Larva	Larvicidal	Maize	[83]
	Myristica fragrans	*T. castaneum*	larva	Larvicidal	Maize	[165]
	Piper nigrum	*T. castaneum*	larvae	Larvicidal	Maize	[148]
	Eucalyptus camaldulensis, *E. viminalis*, *E. microtheca*, *E. grandis* and *E. sargentii*	*T. confusum* and *T. castaneum*	larvae	Larvicidal	Maize	[166]

Table 1. *Cont.*

Method	Product Common Names	Insect Pest	Insect Stage	Mode of Action	Crops	References
	Cuminum cyminum	*C. chinensis* and *S. oryzae*	larvae	Larvicidal	Maize	[83]
	Crithimum maritimum	*O. surinamensis*, *S. granarius* and *S. oryzae*	larvae	Larvicidal	Maize	[83]
	Zanthoxylum planispinum	*Tribolium castaneum*, *Lasioderma serricorne*, and *Liposcelis bostrychophila*	Adult	Contact toxicity and repellent	Maize	[167]
Long-lasting Insecticide-incorporated Netting (LLIN)	LLIN	*Tribolium castaneum*, *T. variabile* and *Rhyzopertha dominica*,	Adult and larva	Reduced movement and dispersal	Maize	[93]
Insect Growth Regulator (IGR)	Methoprene	*Rhyzopertha dominica*, *Tribolium castaneum* and *Sitotroga cerealella*	larva	Affect development, reproduction and behavior	Maize	[94]
Combined methods	methoprene + controlled aeration	*Plodia interpunctella*, *Tribolium castaneum*, *Cryptolestes ferrugineus* and *Rhyzopertha dominica.*	Larva	Affect development, reproduction and behavior	Maize	[100]
	Wood vinegar + deltermethrin	*Sitophilus oryzae*	Larva and adult	Toxicity	Maize	[77]
	Hypoxic nitrogen + Silo	*S. granaries*	All stages	Toxicity	Maize	[105]
	Spinosad + diatomaceous earth + *Trichoderma harzianum*	*Sitophilus oryzae*	All stages	Toxicity	Maize	[120]
	crystalline silica + abamectin	*P. truncatus*	Adult and larva	Toxicity	Maize	[168]
	Hermetic bag + varieties	*Sitophilus zeamais*, *Sitotroga cerealella*, *Tribolium castaneum* and *Cryptolestes* spp.	Adults	Reduced population	Maize	[169]
	Resistant varieties + Teretrius nigrescens	*P. truncatus*	Adult and larva	Reduced population	Maize	[170]
	Metarhizium anisopliae + diatomaceous earth (DE)	*Rhyzopertha dominica*, *Sitophilus oryzae* and *Tribolium confusum*, *L. paeta*, *C. ferrugineus* and *T. castaneum*	Larva and adult	Toxicity	Maize	[119]
	Beauveria bassiana + diatomaceous earth + abamectin	*T. castaneum*	Larva	Toxicity	Wheat	[171]
Cultural methods	Removal of infested residues	*Most primary storage insect pests like S. zeamais* and *P. truncatus*	All stages	Reduced population	Maize and Beans	[110,172]
	Increase in aeration airflow rate	*Sitophilus* spp. and *Rhyzopertha dominica*	Adult	Reduced populations.	Maize	[104]
	Grains petiodic disturbance	*Sitophilus* spp. and *Acanthoscelides obtectus*	Adults	Reduced populations	Maize and Beans	[108]
	Resistance varieties	*P. truncatus*	Adults and larva	Reduced population	Maize	[107]
Biological Control	*Teretrius nigrescens*	*P. truncatus*	Adult	Predation	Maize	[109]
	Theocolax elegans	*Sitophilus* spp., *Rhyzopertha dominica*, *Stegobium paniceum* and *Sitotroga cerealella*	larva	Predation	Maize	[110]

Table 1. *Cont.*

Method	Product Common Names	Insect Pest	Insect Stage	Mode of Action	Crops	References
	Beauveria bassiana + Isaria fumosorosea	*Sitophilus* sp.	Larva and adult	Parasitism	Maize	[111]
	M. anisopliae + I. fumosorosea	*S. granarius* and *S. oryzae*	Larva and adult	Parasitism	Maize	[173]
Hermitic storage	Metal silo and Super Grain IV-R bags	*All storage insects*	All stages	Asphyxiation	Maize	[116]
	PICS bags	*P. Truncatus*, *S. zeamais* and *Zabrotes subfasciatus*	All stages	Asphyxiation	Maize and Beans	[117,174]
Zerofly bags	Polypropylene + deltamethrin	*S. oryzae* and *T. castaneum*	Larva and adults	Toxicity	Maize	[6,47]
Mass trapping	4,8-dimethyldecanal and kairomone	*Tribolium castaneum*	Adult	Attraction	Maize	[126]
Ionizing Radiation	neutron irradiation	*Plodia interpunctella*	Adult	Toxicity	Maize	[129]
	radiofrequency heating	*Various storage insects*	All stages	Toxicity	Maize and Beans	[130]
	microwave heating	*Tribolium castaneum*	Adult	Toxicity	Maize	[175]

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