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The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2021; SP-10(6): 306-314

www.thepharmajournal.com
Received: 22-04-2021
Accepted: 24-05-2021

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Management of agricultural insect pests with physical control methods

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Abstract
Physical control is one of the main approaches to crop protection against insects, the others being chemical, biological and cultural.). From theoretical and technical points of view, all of these approaches have limits that make them more or less suitable for control of a given pest. In practice, the relative merits of each approach are also weighed against numerous factors before an actual decision is made regarding the most appropriate methods to be implemented. A majority of agricultural commodities are protected using chemical control but ideally, all components and technologies should be blended optimally and harmoniously into an integrated pest management (IPM) program. Ideally integrated pest management should rely on an array of tactics. In reality, the main technologies in use are synthetic pesticides. Because of well documented problems with reliance on synthetic pesticides, viable alternatives are sorely needed. Physical controls can be classified as passive (e.g. trenches, fences, organic mulch, particle films, inert dusts and oils), active (e.g. mechanical, polishing, pneumatic, impact and thermal) and miscellaneous (e.g. cold storage, heated air, flaming, hot water immersion). Some physical methods such as oils have been used successfully or pre-harvest treatments for decades. Another recently developed method for pre-harvest situations is particle films. As we move from production to the consumer, legal constraints restrict the number of options available. Consequently, several physical control methods are used for post-harvest situations. Two noteworthy examples re the entoleter, an impacting machine used to crush all insect stages in flour and hot water immersion of mangoes, used to kill tephritid fruit fly immature in fruit. The future of physical control methods will be influenced by socio-legal issues and by new developments in basic and applied research.

Keywords: management, agricultural insect pests, physical control methods

1. Introduction

There is need to reduce the negative impacts of pest control methods on the environment. Increased concerns about the potential effects of pesticides on health, the reduction in arable land per capita (Novartis, 1997) [51] and the evolution of pest complexes likely to be accelerated by climate changes also contribute to change in plant protection practices. Insecticides are still widely used; however, more than 540 insect species are resistant to synthetic insecticides (Metcalf, 1994) [46]. Other drawbacks of synthetic insecticides include resurgence and outbreaks of secondary pests and harmful effects on non-target organisms (Panneton, 2001) [20]. His situation creates a demand for alternative control methods, including physical controls. Metcalf *et al.* wrote physical controls "are in general costly in time and labour, often do not destroy the pest until much damage has been done and rarely give adequate or commercial control". However, recent advances in physical controls and the restrictions place on many chemical controls have resulted in a notable increase in research and application of physical controls. In physical control methods, the physical environment of the pest is modified in such a way that the insects no longer pose a threat to the agricultural crop. This can be achieved by generating stress levels ranging from agitation to death or by using devices such a physical barriers that protect produce or pants from infestation. Many physical control methods target an ensemble of physiological and behavioural processes, whereas chemical methods have well defined and limited modes of action. Physical control methods are grouped under two main classes, passive and active; a miscellaneous category groups those that do not readily fit this classification. The active class is further subdivided into mechanical, thermal and electromagnetic techniques. Passive methods do not require additional input after establishment to be effective over a given period. The efficacy of active methods depends on continued input over the period of control. The level of control achieved is related to the amount and intensity of the input. Effective physical control methods protect plants during the entire season from emergence to postharvest. However, postharvest conditions are better suited to physical control methods because the environment is rather confined, the material is of high economic value and the use of insecticides is frequently inappropriate or even unlawful. Physical control methods, such as cold, heat and ionizing radiation, are used extensively as postharvest quarantine treatments where disinfestations of a given pest at a predetermined level of control must be achieved (Hallman, 2001) [29, 31].

This approach refers to the use of a variety of physical or mechanical techniques for pest exclusion, trapping (in some cases similar to the behavioural control), removal, or destruction (Webb and Linda 1992, Gamliel and Katan 2012, Gogo *et al*. 2014, Dara *et al*. 2018) [23, 26, 80]. Pest exclusion with netting or row covers, handpicking or vacuuming to remove pests, mechanical tools for weed control, traps for rodent pests, modifying environmental conditions such as heat or humidity in greenhouses, steam sterilization or solarisation, visual or physical bird deterrents such as reflective material or sonic devices are some examples of physical or mechanical control. In the last decades, chemical means of pest control in bulk products have been the most important methods of control. However, the development of resistance is a threat to phosphine fumigation in grain. Recently, dichlorvos (DDVP) used in insecticidal fogs and evaporation strips was banned by the European Union due to the wish to reduce residue levels on treated products. Furthermore, new concerns on fluoride residues prompted the European Union to reduce the tolerated maximum residue levels in nuts, grain and grain products and dried fruits which reduced the availability of sulfuryl fluoride in stored product protection mainly to structural treatments. Because stored product protection is a rather small market for pesticides wit stiff requirements regarding workers safety and residue levels, a significant increase in chemicals available for this purpose seems not probable in the near future. The lack of chemical means of pest control increases the need to prevent and detect pests and renders chemical methods of pest control more attractive. Physical methods are important means to prevent, detect and control stored product pest within the concept of Integrated Pest Management. If one thinks of stable food such as grains or pulses, cleaning, drying and cooling are physical processes essential to keep durable product in good quality during prolonged storage periods (Vincent *et al*. 2002) [79]. The drying process could be utilized to control pest arthropods that may have found their way into the grains provided that a uniform temperature above some 55 °C is achieved for 60 min or 60 °C for about one minute. Cooling to temperatures below 13 °C prevents insect development and is thus another method to provide safe storage conditions (Fields, 1992) [20], this method is used for rain storage not only by organic farmers and its importance may increase due to the loss of dichlorvos emitting trips for stored product moth control in 2007. Insect proof or hermetic storage structures prevent the immigration of pests and thus could reduce efforts for pest control provide the stored goods are free of living insects at the time of reception. Insect proof packaging is the only means of pest prevention on the way from processing to consumption, e.g. some chocolate bar producers have improved the quality of their packages in recent years hanging from a wrap with aluminium foil and paper to a gas tightly sealed plastic film. A recent test of different packaging films to the attack by various stored product insects was published (Riudavets *et al*. 2007). Generally, extreme temperatures and mechanical methods are used for pest control at present. A vacuum can be applied to products packed into a flexible structure in order to remove oxygen from the inner granular space. Especially at higher product temperature this can lead to fast and reliable pest control as reported from cocoa storage (Finkelman *et al*. 2003).

2. Mechanical and physical method to control the insect pest from plants

2.1. Handpicking method

Hand picking is kind of excluding technique which is not practicable for large scale pest management program; however, it can be practiced for small scale pest management program like in lawns, kitchen gardening, small-scale tunnel farming, inside greenhouses. This technique is the most practical way in certain conditions like, when cheap labour is available, insects and their eggs/egg-masses are large and conspicuous, and insects are too sluggish, have congregating behaviour and are easily accessible to the pickers. Handpicking of slow moving and visible larvae of *Pieris brassicae* L. (Cabbage butterfly) (Lepidoptera: Pieridae), lemon butterfly *Papilio demoleus* Linn. (Lepidoptera: Papilionidae), semiloopers and loopers (Lepidoptera: Noctuidae), cutworms (Lepidoptera: Noctuidae) and red pumpkin beetle *Aulacophora foveicollis* Lucas (Coleoptera: Chrysomelidae) and visible eggs/egg masses of cabbage butterfly, armyworm *Spodoptera* (Guenee) and *Mythemna* (Ochsenheimer,) spp. (Lepidoptera: Noctuidae)], and borers Pyralid borers, Noctuid borers, Crambid borers etc. (Lepidoptera) is an easiest, direct and excellent method of controlling them especially when their infestation is restricted to only a few plants. In case of pink bollworm *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae) infestation in cotton, the rossetted flowers having pink bollworm larvae inside are picked and destroyed. Collection and destruction of egg masses of top borer *Scirpophaga nivella* F. (Lepidoptera: Pyralidae) in ratoon and seasonal sugarcane (*Saccharum officinarum* L.) crop reduces its endemic outbreak and losses (Saha and Dhaliwal 2012; Arif, 2019) [5, 58].

2.2. Bagging, screening and barriers

Bagging, screening and barriers installation is also considered very useful for protecting the crop and fruits from attack by insect pests as well as for keeping away the insect pests which either act as carrier or vectors of various fatal diseases in animals and man or create nuisance for man. For example, field bags' dragging in the maize (*Zea mays* L.) or sorghum (*Sorghum bicolor* L.) field and sugarcane (*S. officinarum* L.) ratoon crop (April/May) to collect sugarcane pyrilla *Pyrilla perpusilla* Walker (Homoptera: Lophopidae) can reduce the chances of their massive migration from maize/sorghum to sugarcane and population build-up of pyrilla at the initial growth stage of sugarcane ratoon crop. Such type of field bags can also be used for the mass collection of various grasshoppers (Orthoptera: Insecta), bugs (Hemiptera: Insecta), crickets (Orthoptera: Insecta) and other minute, small and large insects harbouring vegetation (Arif, 2019) [5].

2.3. Wrapping

Wrapping of individual fruits with paper bags, polythene bags, butter-paper bags or net bags protects 95% of these fruits from the infestation of fruit flies. Covering whole small trees with any transparent material can reduce the attack of various insects' pests. Construction of water filled or dust (insecticide) treated drench between wheat (*Triticum aestivum*

L.) field and burseem (*Trifolium alexandrium* L.) field can reduce the migration of armyworm (*Spodoptera* spp.) larvae from wheat to berseem fields and minimize their damage on berseem. Similar type of drenches can reduce the migration of bands of locust hoppers [*Schistocerca gregaria* (Forskål) (Orthoptera: Acrididae)] from the breeding placed to nearest field crops (Arif, 2019) [5].

2.4. Netting method

In recent studies, special attention is given to insect exclusion netting systems in apple production. The first netting system was designed in France in 2005 and in 2008 it was introduced in Italy. In both countries, a high level of efficacy of nets was observed against Codling moth. Also, this method enables a significant reduction in pesticide use without any major risks for apple production (Alaphilippe *et al*. 2016) [2]. (Pajac Zivkovic *et al.* 2016) [53] tested the effectiveness of insect exclusion netting systems in preventing the attack of Codling Moth on apple fruits in Croatia. While the netting system prevents the entry of insect pests, it also serves as a barrier to beneficial insects (e.g., ladybugs, true bugs and syrphid flies) which could negatively affect natural pest control services.

2.5. Mulching materials and natural enemies

In the present study, the populations of natural enemies mainly *Cheilomenes* sp. *and A. aurantia* were similar on both the mulch treated plots and the control, suggesting that the mulch did not have any adverse effect on these natural enemies compared to the chemical insecticide. but reduced the insect population in the field including their natural enemies. As biological control agents, any decrease in their population can adversely affect the pests they assist in controlling on the crop plant. *Cheilomenes* sp. is a natural enemy of *A. gossypii*, *B. tabaci* and *T. tabaci* as reported in earlier studies by (Mochiah *et al*. 2011a, 2011b) [47, 48]. *A. aurantia* population also showed the same trend as *Cheilomenes* sp. and *S. coleoptrata,* hence the mulching materials were also effective as compared to the control in conserving the population of natural enemies (Johnson *et al*. 2004) [32].

2.5.1. Organic mulch

Straw mulch indirectly affects Colorado potato beetle populations and significantly reduces damage (Zehnder and Hough-Goldstein, 1990) [83] by favouring several species of its egg and larval predators: *Coleomegilla maculata*, *Hippodamia convergens*, *Chrysopa carnea*, and *Perillus bioculatus*. Although the yield of potato fields is higher in mulched than in non-mulched plantings or when straw mulch is incorporated into an insecticide program (Brust, 1994) [12], the cost of using straw mulch may be prohibitive to nonorganic growers (Ferro, 1996) [19].

2.6. Flooding

Flooding is used as a standard agronomic practice in cranberry production, and its insecticidal value against a number of insects was recognized more than 70 years ago. Two types of management are used in cranberry plantations. “Early water” is defined as a bed where the winter flooding, used to protect the plant from winter injury, is removed in March without further flooding. “Late water” is flooding for 30 days from mid-April to mid-May to manage cranberry fruit worm, *Acrobasis vaccinii*, southern red mite, *Oligonychus ilicis*, and early-season cutworms. Late water significantly reduced cranberry fruit worm egg populations compared to early water. One additional benefit is that late water controls cranberry fruit rot. Flooding can only be used where water is abundant and where the crop would tolerate it for a prolonged period (Averill *et al*. 1997) [6].

2.7. Hermetic storage technology (Airtight)

Hermetic simply means ‘airtight’. The origin of hermetic storage dates back to antiquity. Hermetic storage (HS) technology has emerged as a significant alternative to other methods of storage that protect commodities from insects and moulds Hermetic storage is based on the principle of generating an oxygen-depleted, carbon dioxide-enriched interstitial atmosphere caused by the respiration of the living organisms in the ecological system of a sealed storage structure (Vachanth *et al.* 2010; Obeng-Ofori, 1995; De Bruin and Murali, 2006; Donahaye *et al.* 2001;Chauhan and Ghaffar, 2002) [15, 17, 19, 53, 77].

2.8. Pheromone traps

Are being practiced successfully for the monitoring, trapping, mating disruption and management of various insect pests.

Table 1: Pheromone trap used against different pest

Insect common name	Scientific name	Types of pheromone	Family	Order
Gypsy moth	*Lymantria dispar*	Disparlure	Lymantriidae	Lepidoptera
Pink bollworm	*Pectinophora gossypiella*	Gossyplure	Gelechioidea	Lepidoptera
cotton grey weevil	*Anthonomus grandis*	Grandlure	Curculionidae	Coleoptera
Pine beetle	*Dendroctonus ponderosae*	Frontalin bravicomin	Curculionidae	Coleoptera
Oriental fruit fly	*Bactrocera dorsalis*	Methyl eugenol	Tephritidae	Diptera
European chaffer	*Rhizotrogus majalis*	Amlure	Scarabeidae	Coleoptera
Melon fruit fly	*Bactrocera cucurbitae*	Cuelure	Tephritidae	Diptera

(Arif *et al*. 2019) [5]

2.9. Light traps

Associated with toxic compound are practiced for the trapping and killing of nocturnal insect pests (Arif *et al*. 2019) [5].

Table 2: Light trap to attract the different species

Common name	Scientific name	Different crop	Family	Order
American Bollworm	*Helicoverpa armigera*	Mungbean, Gram, Wheat, Vegetables, Cotton, Maize	Noctuidae	Lepidoptera
Armyworm	*Spodoptera litura*	Mung bean, Gram, Wheat, Vegetables, Cotton	Noctuidae	Lepidoptera
Termites	*Microtermes* Spp.	All crops, vegetables and ornamentals	Termitidae	Isoptera
Green Bug	*Chinavia hilaris*	Mungbean, Gram, Vegetables, Cotton	Pentatomidae	Hemiptera
Grey weevil	*Myllocerus viridanus*	Mungbean, Cotton	Curculionoidea	Coleoptera

(Abbas *et al*. 2019) [1]

Table 3: Management of agricultural insect pest with physical control method

S. No.	Scientific name	Specific physical management practices	References
1	*Aleurodicus dispersus* (Spiralling Whitefly)	Yellow sticky traps to trap whitefly and the removal of leaves to control of nymphal and pupal stages of whiteflies	(Barbedo, 2014) [7]
2	*Myzus persicae* (Aphid)	Reduces the attractiveness of hosts	(Ben Issa *et al*. 2017) [9]
3	*Chilo partellus* (Stem borer)	The push-pull strategy approach successful management of stem borer	(Bhattacharyya, 2017) [11]
4	*Bactrocera dorsalis* (Oriental fruit fly)	Methyl eugenol pheromone trap use to control of fly	(Vargas *et al*. 2010) [79]
5	*Bonagota salubricola* (Apple leaf roller)	Bagging of fruit to control	(Teixeira *et al*. 2011) [73]
6	*Liriomyza sativae* (Leaf miners), *Thrips tabaci* (Onion thrips), and *Bemisia tabaci* (Whiteflies)	The white nets and floating row covers to reduce population and successful management	(Majumdar *et al*. 2010) [40]
7	*Papilio demoleus* (Lemon butterfly)	Collection of infested leaves and destroying by burning or burying under the soil Hand-picking and destruction of the various stages of the butterflies	(Nath and Deka, 2020) [60]
8	*Spodoptera litura* (Tobacco cutworm)	Hand picking excluding technique use to control	(Saha and Dhaliwal., 2012) [61]
9	Leaf miners (*Phyllocnistis citrella*), scale (*Aonidiella aurantii*), mites (*Phyllocoptrata oleivora*)	Mineral oils have protruding potential to control	(Beattie and Hardy, 2005; Leong *et al*. 2012) [8]
10	Mango Stem Borers	Stem wrapping with a nylon mesh during May-August helps in capturing freshly emerging adult beetles	(Reddy *et al*. 2014) [59]
11	(Whitefly)	The effect of nylon net as physical barrier in controlling whitefly in chili	(Salas *et al*. 2015) [62]
12	*Bemisia tabaci* (Sweet potato whitefly)	Free floating covers effective physical barrier	(Shah *et al*. 2019) [64]

3. Physical methods in pre and post-harvest situations

3.1. Pre-harvest control measures

3.1.1. Exclusion barriers

Insect exclusion screening is probably the single most important physical control method developed in the last century. Following the invasion of virus bearing whiteflies, tomato crops in the entire Mediterranean region could not be grown in open fields from late spring through fall. The development of screens allowed tomatoes to be produced year-round, and the use of screens has become a standard pest management practice worldwide. This form of physical control has proven cost-effective both for consumers and growers (Weintraub and Berlinger, 2004) [84]. Usage of exclusion screening is not limited to the traditional greenhouse crops; orchards are increasingly being covered to prevent pests from gaining access to trees. Netting which excludes fruit flies has proven to be an economically effective method of protecting peaches and nectarines, increasing yield quantity and quality (Nissen *et al*. 2005a, b) [51, 52]. Certain diseases, such as papaya dieback, can only be controlled by covering plantations with coarse white nets to limit vector movement (Franck and Bar-Joseph, 1992) [24]. Bananas are grown under screening in many parts of the world. Another example of an exclusion barrier in north eastern North America involves the simultaneous management of weeds in apple orchards and two insect pests, plum curculio (*Conotrachelus nenuphar*) and apple sawfly (*Hoplocampa testudinea*). Both insects lay their eggs in fruitlets where the larvae develop. In late June infested fruitlets fall to the ground and mature larvae enter the soil to pupate. In field experiments over a four-year period, cellulose sheeting prevented most weeds from emerging (Benoit *et al*. 2006) [10]. Total weed density was significantly lower in plots covered with cellulose sheeting as compared to control (no sheeting) plots. However accumulation of soil on the sheeting allowed a few weeds to grow. Likewise, emergence of adults from fallen apples covered with a cage was significantly reduced for both plum curculio and apple sawfly. However, some individuals completed their development and successfully overwintered on the sheeting. For example, in spite of cellulose sheeting, the percentage of plum curculio emergence varied from 0.7% to 18.9% in one orchard compared to 9.3% to 63.5% in the control. Over the years, the integrity of cellulose sheeting has been challenged by accumulation of plant debris and water, causing biodegradation of the sheeting, allowing weeds and insects to penetrate through damaged surfaces.

3.1.2. Pneumatic control

In pneumatic control, insects can be dislodged from plants with negative (aspiration) or positive (blowing) air pressure, then killed by a system of turbines or collected and killed upstream in a dedicated system of the blower. With respect to the plant to be protected, distinction must be made between flexible and rigid plants. In the latter, only blowing can be used efficiently, otherwise the plant can be damaged by the machinery. Reviews on pneumatic control from an entomological perspective have been provided by Vincent and Boiteau, 2001) [20, 35, 37, 78], (Weintraub and Horowitz, 2001 and Vincent, 2002) [79, 85]. Reviews discussing engineering aspects were published by (Khelifi *et al*. 2001) [37] and (Lacasse *et al*. 2001) [37, 39]. Most papers thus far published on pneumatic control have focused on the tarnished plant bug (*Lygus lineolaris*) on strawberry (a flexible plant), Colorado potato beetle (*Leptinotarsa decemlineata*) on potato (a semi-rigid plant), pea leaf miner (*Liriomyza huidobrensis*) in celery and whiteflies (*Bemisia tabaci*) on potatoes and melon.

3.1.3. Shredding of apple leaves

Physical control methods typically affect a broad number of pest species; however, few studies have range of insects have been shown to be affected, including psyllids and rust mites (Puterka *et al*. 2000) [38], aphids, spider mites and leafhoppers (Glenn *et al*. 1999) [27]; various Lepidoptera (Knight *et al*. 2000; Unruh *et al*. 2000) [38] and beetles (Lapointe, 2000; Thomas *et al*. 2004) [77, 78]. In addition to the disruption of arthropod pests, some fungal pathogens are also killed and heat stress is reduced in trees (Thomas *et al*. 2004) [78].

3.1.4. Dusts
Dusts and powders have been known, for decades, to desiccate arthropods; as such, they were used directly on pests and often included in pesticide formulations pre-1945. What is novel is the use of kaolin (aluminium silicate hydroxide) in a particle film technique (Glenn *et al*. 1999) [27]. With this technique, plant surfaces are coated with a fine layer of kaolin particles which disrupt arthropod recognition of plant surfaces, resulting in reduced oviposition and feeding. A wide range of insects have been shown to be affected, including psyllids and rust mites (Puterka *et al*. 2000) [38], aphids, spider mites and leafhoppers (Glenn *et al*. 1999) [27]; various Lepidoptera (Knight *et al*. 2000; Unruh *et al*. 2000) [38] and beetles (Lapointe, 2000; Thomas *et al*. 2004) [77, 78]. In addition to the disruption of arthropod pests, some fungal pathogens are also killed and heat stress is reduced in trees (Thomas *et al*. 2004) [78].

4. Post-harvest control measures
4.1. Mechanical injury
Insects in stored grain or cereal flour are often killed mechanically during transportation by pneumatic conveyors as the result of violent repeated shocks of kernels against metal ducts. In flour mills, both grain and flour can be disinfested by passing through "entoleters" that use centrifugal force to throw the grain against a steel surface (Fields *et al*. 2001) [22]. When this equipment is activated on the grain stream prior to milling, infested kernels break apart and are separated from intact kernels. This equipment is most often used to kill insects or eggs infesting fresh flour before its packaging or bulk storage (Stratil *et al.* 1987) [68].

4.2. Wash and wax
Fruit coatings and waxes are known to function as modified atmosphere treatments against tephritid fruit fly immatures in fruit by reducing oxygen and raising carbon dioxide levels inside fruit (Hallman, 1997) [30]. However, when coatings are applied to fruit infested with small surface pests the mode of action is primarily physical; the organism becomes adhered and unable to move. Coatings form a major component of an integrated treatment against the mite *Brevipalpus chilensis* on cheriinoya, lime and passion fruit, from Chile to the USA (Animal and Plant Health Inspection Service, 2007) [4].

4.3. Ionizing irradiation
Exposure of commodities to ionizing radiation at absorbed doses of 50-400 Gy causes physical breaks in molecules, especially larger ones such as DNA, resulting in their inability to function correctly and prevention of continued development (Hallman, 2001) [29, 31]. Although most quarantine pests are not killed rapidly by doses in this range they will not successfully reproduce.

5. Electric field-based pest management approaches
The electric field screen, first introduced in 2006, is an air-shielding apparatus based on the principles and techniques of applied electrostatic engineering (Matsuda, 2006) [41]. Initially, the apparatus was presented as a new device to capture the airborne conidia (spores) of phytopathogenic fungi during crop cultivation in a greenhouse. As the research progressed, the targets of the screen were expanded from fungal spores to include capture the airborne conidia (spores) of phytopathogenic fungi during crop cultivation in a greenhouse. As the research progressed, the targets of the screen were expanded from fungal spores (Shimizu, 2007; Takikawa, 2014) [66, 69] to include flying insect pests (Tanaka, 2008; Matsuda, 2011) [43, 74], pollen grains that cause pollenosis (Takikawa, 2017) [71] and fine particles of tobacco smoke (Takikawa, 2017; Matsuda, 2018) [44, 45, 71] by optimising the structure of the electric field screen and its capture capabilities. Advances in electric field screen technology have allowed broader application of the device, from agricultural field, e.g. crop production, processing and storage to environment field and public health science. The two types of electric field screen used for insect capture were first reported in 2008 (Tanaka, 2008) [74] and 2011 (Matsuda, 2011) [43]. Subsequently, the focus of electric field screen research has been to explain the mechanisms of insect capture (Matsuda, 2012; Kakutani, 2012; Nonomura, 2012) [42, 53] and develop electric field screen devices for pest control (Takikawa, 2015; Takikawa, 2016; Kakutani, 2017; Takikawa, 2020) [35, 70, 72, 73]. These works provide an experimental basis for an alternative to conventional pest control. In two of the works mentioned above (Matsuda, 2011; Nonomura, 2012) [43] we realised that insects find entering the static electric field of a single-charged dipolar electric field screen highly aversive. Avoidance behaviour has been detected in 82 insect species, belonging to17 orders,42 families, and 45 genera which shed light on a new function of electric field screens; however, the question of how insects perceive an electric field remain unsolved and only one recent study has addressed this issue (Matsuda, 2015) [70]. Additional studies are eagerly awaited. Dynamic electric fields also have potential for novel physical measures to control insect pests. Two works (Kakutani, 2018; Matsuda, 2018) [36, 44, 45] have been reported unique apparatus that cause an arc discharge to hit insects that enter a dynamic electric field. Arc discharge generating techniques may provide a new tool for detecting and dismembering insects nesting in dried gain or selectively killing flies emerging from underground pupae, which may be useful or organic farming. The corona discharge exposure technique has potential as a non-distractive inspection system to detect pests nesting in dried cereal products, based on the difference in conductivity between dried cereal grains and living pests. This is one of the main themes in this special issue.

6. Management of plant and artopod pests by deer farmers in florida
Deer farming in the United States is a young and growing industry, with 7,828 deer farms in the country in 2007 (Anderson *et al*. 2007; Devuyst, 2013) [3, 19]. A third of these farms (estimated at 2,639 farms) are hunting preserves, and the remainder are breeding operations, venison farmers (typically fallow and red deer, and elk), and scent collectors. In Florida, there are approximately 400 deer farms (Anderson *et al*. 2007) [3]. Deer farming throughout the United States, especially in Florida, represents a lucrative industry as deer can be farmed on land that is not suitable for other forms of

livestock or agriculture, can yield biproducts from animals such as venison, antlers, and hides, and can encourage tourism growth through guided tours and hunts (Brooks *et al*. 2015) [13]. Arthropods that affect deer health include horse and deer flies, mosquitoes, ticks, and Culicoides biting midges (Diptera: Ceratopogonidae). Nuisance biting and vector-borne pathogen transmission by these arthropods can have economic impacts on the deer farming industry, just as they do in other livestock systems. Vector-borne diseases may lead to decreased fitness in livestock, which results in decreased productivity as well as morbidity and mortality (Steelman, 1976) [67]. Some of these arthropods spread zoonotic pathogens, which also have impacts on public health, such as the pathogen that causes Lyme disease, which is transmitted by the tick, *Ixodes scapularis* (Say) (Ixodida: Ixodidae). Horse and deer flies, or tabanids (Diptera: Tabanidae), represent serious deer pests, which could potentially result in economic losses through lowered livestock fitness (Perich *et al*. 1986) [58], due to avoidance behaviour, blood loss, localized skin reactions, secondary feeding in wounds, and myiasis as well as mechanical transmission of pathogens (Foil and Hogsette, 1994) [23]. Tabanids transmit these pathogens to and among deer. *Bacillus anthracis* is the causative agent of anthrax. Infection occurs when *B. anthracis* spores are ingested or inhaled during browsing or ingestion of soil, the spores germinate and replicate, the host dies, and then the blood of the host is exposed to oxygen resulting in contamination of surrounding vegetation and soil (Blackburn *et al*. 2014) [12]. Twenty-one tabanid species have been documented to mechanically transmit *B. anthracis* in a laboratory setting (Ganeva, 2004) [26], Mosquitoes (Diptera: Culicidae) transmit various pathogens to humans and other animals. Eastern equine encephalitis (EEE) virus, which is a zoonotic pathogen transmitted by mosquitoes, has been detected in deer (Schmitt *et al*. 2007) [64]. EEE virus is transmitted by the *Culiseta* genus between birds and between birds and mammals by species in the genera Aedes and Coquillettidia. Mammals such as deer, humans, and horses are dead-end hosts; the disease caused by the virus is often fatal. In deer, symptoms include lethargy, confusion, poor coordination, tilted head, circling, blindness, paralysis, loss of fear, respiratory difficulties, emaciation, and death. Additionally, mosquitoes of the genus Anopheles transmit deer malaria, *Plasmodium odocoilei* (Haemosporida: Plasmodiidae), which reduces survival in fawns that become infected early in life (Guggisberg *et al*. 2018) [29]. Tick species vector numerous pathogens to livestock and other animals. For example, ticks in the genus Dermacentor are vectors for *A. marginale*, the pathogen described earlier that also is transmitted by tabanids. In the United States, *A. americanum* is the major *Theileria cervi* (Piroplasmorida: Theileriidae) vector, causative agent of theileriasis, to white-tailed deer. Theileriasis is a hemolytic disease, which, while relatively common in deer, mostly affects immunocompromised or translocated animals (Cauvin *et al*. 2019) [15]. Culicoides biting midges are common throughout the United States and transmit several important livestock diseases that make their control vital in and around livestock facilities. For example, blue tongue virus (BTV) and epizootic hemorrhagic disease virus (EHDV) can impact fitness of infected animals, as well as result in mortality (Haigh *et al*. 2002) [30]. IPM use by deer farmers to control plant or arthropod pest populations in Florida has not been reported to date. With deer farming becoming an increasingly common industry in the United States, initial examination of the currently implemented management techniques of deer farmers is a crucial component in future development of management practices to effectively control pests while mitigating pesticide resistance development and protecting animal health on these facilities. The purpose of this research was to: 1) assess deer farmer perception about pesticide use; 2) determine the type of pesticides used; 3) quantify the frequency with which pesticides are used; and 4) evaluate the current knowledge about pesticide resistance and incorporation of resistance mitigation tactics by deer farmers. This information was obtained through a Qualtrics survey delivered to deer farmers in Florida, and provided insight into behaviour, attitudes, and knowledge of Florida deer farmers towards pesticides as well as allowed deer farmers to self-evaluate their pesticide usage level. Additional questions were focused on Culicoides biting midge management, as these small biting flies are important pathogen vectors in Florida and pose a significant threat to the industry (McGregor *et al*. 2019) [47].

7. Conclusion

Today, there is a common will worldwide to limit the pest problems at all steps of the pre- and postharvest food chain by expanding IPM applications. If managers fully considered the ‘value-added’ aspect of IPM implementation instead of the simpler conventional/chemical pest control tactics, we believe that physical control measures would be more broadly used. However, legislation, such as the phasing out of the fumigant methyl bromide, is pushing the search for safer alternative control measures. The implementation of physical control measures in food storage or processing facilities needs a certain amount of preparedness and investment. This is especially true for the monitoring and the assessment of the indicators of pest presence and population dynamics trends with time. Application of physical control measures requires the recruitment of trained personnel with high levels of knowledge about bionomics and behaviour of the major pest species. More often, starting an IPM program requires an improvement of the design of the structure and the modification of material layout to facilitate the implementation of different components. There are generally moderate costs associated with optimization of the facilities. After this first stage, the practical application of an IPM program should be continuously updated by the use of modern tools facilitating the sanitation procedures as well as the interpretation of monitoring data. The other obstacle to application is to fit the recommendations included in the codes for good hygiene and sanitation practices to the specific constraints and needs of a particular food processing or manufacturing facility. This difficulty may be overcome with the increasing availability of computer software dedicated to the training of IPM practitioners or giving valuable advice for correct practical implementation and customization of IPM plans. These decision support systems may also contain expert knowledge accessible to the questions and inquiries from the users. Although it is easy to demonstrate that the balance iii investment/efficiency is favourable in most cases, managers are often reluctant to invest a lot of money in IPM program development. However, since the publication of a new regulation dealing with food quality and safety assurance in all food production chains, the position of managers about the IPM system implementation will have to change for the benefit of all. In general physical methods are established and widely used methods in stored product IPM. While they may not be feasible in all cases, the loss of chemical compounds may lead to a revival or increased utilisation of physical methods. Improvements in the structural design of bakeries, pasta factories and other processing plants could help to prevent re-infestation after processing seps leading to pest control such as extrusion, drying or milling. Heat treatments could gain importance for the residue-free treatment of machinery or structures.

8. References

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