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Application of Controlled Atmospheres and Fumigation in Control of Psocids

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Abstract: Small, polyphagous insects are generally ignored in most grain storage systems; however, psocids have recently become a serious problem in food facilities and stored products in many countries and regions. Fumigant methyl bromide has been used around the world since the 1930s as a quarantine treatment for plants and to control insects in buildings and commodities. With the ban of methyl bromide for controlling stored product pests, numerous chemicals are being considered as alternative fumigants. Candidate fumigants include phosphine, sulfuryl fluoride, carbonyl sulfide, carbon disulfide, ethyl formate, ethylene oxide, hydrogen cyanide, methyl iodide, sulphur dioxide, methyl formate, and acetaldehyde. Owing to the lack of alternatives that match the combined advantages of phosphine, it is likely that phosphine will remain the major grain fumigant for the foreseeable future. As a friendly and rapid fumigant, ethyl formate also promised controlling stored products pests. Controlled atmospheres with elevated carbon dioxide, low oxygen levels, or a combination of both have been tested and become useful and practical for the control of stored product insects. The potential use of these and other non-toxic and environmentally benign materials as alternatives to currently used fumigants has been widely recognized. Despite numerous reports of resistance to many insecticides, chemical control will continue to play an important role in psocids control programs. Studies on population ecology and resistance development to control treatments are fundamental to the development Integrated Pest Management (IPM) strategies for psocids. This review is mainly to summarize the last decade's application of CA and fumigation in control of psocids and expect to assist in formulating strategies to control these rapidly proliferating pests.

Key words: controlled atmospheres, fumigation, phosphine, ethyl formate, *Liposcelis*

Introduction

Psocids, or booklice, mainly belonging to the genus *Liposcelis*, are serious pests of stored grain in tropical and subtropical Asia [1-3] and have emerged in the 1990s as major pests in Australia [4,5] and China [6]. Their ability to exist for long periods without food and their small size makes them extremely invasive of storage structures. In recent years, there has been a gradual worldwide recognition that psocids pose a series of distinct pest problems in the area of grain storage and stored products [7]. In the last two decades, *Liposcelis* species have been reported as pests in Europe, Canada, Australia, New Zealand and Asia in commercial and domestic situations [3,6,7].

Methyl bromide has been used around the world since the 1930s as a quarantine treatment for plants and to control insects in buildings and commodities effectively. However, routine fumigations of warehouses and storage facilities with methyl bromide have failed to control psocids [8]. The adverse effects of methyl bromide on the atmospheric ozone layer and worker safety issues prompted the enactment of the Clean Air Act by the US Federal government which requires all developed countries eliminate the bulk of their methyl bromide consumption by 2005 [9]. The loss of this important fumigant has forced researchers to find alternatives. Numerous chemicals are being considered as alternative fumigants to control stored product pests, but none are as fast acting as methyl bromide. Candidate fumigants include phosphine, sulfuryl fluoride, carbonyl sulfide, carbon disulfide, ethyl formate, ethylene oxide, hydrogen cyanide, methyl iodide, sulphur dioxide, methyl formate, and acetaldehyde [9-13].

Controlled atmospheres (CA) are also al-

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ternative treatments to the use of methyl bromide for post-harvest insect control. CA with elevated carbon dioxide, low oxygen levels, or a combination of both have been tested and become increasingly useful and practical to control stored product insects. Although commercial use is still limited to a few countries, the potential use of non-toxic and environmentally benign materials as alternatives to currently used fumigants has been widely recognized.

In the last decade, the development of resistance to the most commonly used fumigants such as phosphine and methyl bromide has been well documented [3]. Similarly, extensive use of CA in insect control could lead to selection of insect populations resistant to hypercarbia and hypoxia [6,14,15]. This paper summarizes the past decade's application of CA and fumigation in control of psocids and will present strategies to control these rapidly proliferating pests.

Occurrence and Pest Status of Psocids

Psocoptera is a relatively small order of insects with approximately 4400 species worldwide. Some are adapted to live in food stores, food processing facilities, bulk grain, houses, etc. [16]. Indoors, their occurrence is more frequent in humid environments [17]. There are reports of their presence in various products: coffee and cocoa, tobacco and cereal-derived foods [18]. They are regarded as secondary pests, often overlooked due to their small size and the existence of other more damaging primary pests especially in cereal grains. Nonetheless, when population explosions occur, they can cause considerable economic damage and present a permanent hygienic danger for transferring microorganisms and contaminating material with their excrement and dead bodies. They also cause serious deterioration of the quality, especially of products in the food processing industries. The specific biological traits (small body size, short generation period) contribute to rapid and substantial psocids population growth. The pest status of these insects can be broadly categorized and the mainly three items are as follows: a nuisance as food/commodity contaminant; direct feeding damage of food/commodity; and health risk.

One of the most widely spread members of the order Psocoptera is a minute apterous species *Liposcelis bostrychophila* Badonnel, commonly, but erroneously, known as booklouse. *L. bostrychophila* is commonly found in various processed and unprocessed dry foods in households, granaries and warehouses [7]. Apart from causing measurable damage to stored grains [19], infestations of this psocid can also cause health problems among storage and warehouse workers. This insect feeds continually and reproduces rapidly by obligatory thelytokous parthenogenesis.

Outbreaks of *L. bostrychophila*, together with *L. entomophila* (Enderlein) have been reported in humid tropic countries such as Indonesia, Malaysia, Singapore, The Philippines, Thailand, China and India [3,20,21]. Unlike the above two species of cosmopolitan distribution, *L. paeta* Pearman is prevalent in the tropics and has also been focused in a series of reports [1,22,23].

In China, *L. bostrychophila* and *L. entomophila* have posed an alarming threat to stored products, especially in the storage facilities where CA and insecticide combined treatments are commonly applied. Routine fumigation of warehouses and storage facilities with methyl bromide or the use of insecticides have failed to control these two pests, which can readily reinfest grain in storage after treatments [24]. In addition, rapid development of resistance to chemical and physical treatments has also been reported for *L. bostrychophila* and *L. entomophila* [20].

The distribution and abundance of psocids in Australia's grain storage system has been on the increase over the past decade. *Liposcelis* species have been particularly successful inhabitants of grain stores and are now specifically targeted by integrated control programs. Although considerable effort has been invested in chemical control, psocids continue to thrive in older, unsealed stores. *Liposcelis* infestations are notorious for contributing to violations of Australian grain export legislation that prescribes a zero tolerance to the export of live insects in grain, resulting in serious legal and monetary ramifications. Recently, as a new pest species, *L. decolor* (Pearman) has emerged in eastern and southern Australia, with frequent infestations occurring in both the central bulk-handling systems and in grain stored on farm [22]. Phosphine fumigation that is targeted to control all major stored-grain pests in this country has failed against this species. A search of the literature revealed no published information on the effectiveness of any chemical treatment against this pest, although it has been reported as an emerging pest in several countries around the world, such as China, Croatia, Spain and the Czech Republic [17,21].

Fumigation for Psocids Control

Fumigants hold a specific place in storage of feed and food, especially for pest control. High volatility and penetrability through bulks of stored goods and quick lethal effect on organisms within these products render gaseous substances suitable tools in the scope of integrated pest control. When insect pests survive all human precautions and prevention efforts, large bulks of stored products can be disinfested by use of appropriate fumigants and fumigation techniques. No other approach leads to such instantaneous and feasible pest control without moving the produce, or building up undesired residues.

As a common fumigant of stored products, methyl bromide acts rapidly, controlling insects in less than 48 h in space fumigation, however, because it depletes ozone in the atmosphere, this chemical was banned in 2005 in developed countries. Many alternatives have been tested as replacements for methyl bromide. Among these, phosphine, ethyl formate and essential oils are three promising representatives in psocids prevention [11-13].

Phosphine

With the decreasing use of contact insecticides in recent years due to consumer sensitivity towards residues, fumigation with phosphine has become the worldwide dominant disinfestation treatment and its application in post-harvest grains amounts to 80% in Australia [24]. Owing to the lack of alternatives that match the combined advantages of phosphine, it is likely that phosphine will remain the major grain fumigant for the foreseeable future. Lethal effects of phosphine on egg, nymph and adult stages of *L. bostrychophila* in laboratory showed that phosphine fumigation had different efficacy on the different stages. After 24, 72 and 120 h exposure, LC_{50} of egg were 0.137, 0.045, and 0.035 mg/L, respectively; after 24 h treatment, LC_{50} of nymph varied in the range of 0.004 – 0.007 mg/L, and that of adults was 0.020 mg/L. Exposed to 0.025 mg/L phosphine for 24 h every 10 d, the population was completely controlled [25].

Like many other fumigants, a serious problem with the extensive use of phosphine has been the evolution of resistance in several pest species including psocids [26,27]. In Australia, protocols for phosphine application have failed to control several species of psocid pest and nation-wide surveys have revealed the occurrence of resistance to phosphine in at least four *Liposcelis* psocid species, with the detection of strong resistance in *L. bostrychophila* [22]. While investigating response to phosphine in *L. bostrychophila* populations, an apparent delay in the development of eggs in a resistant strain under fumigation was observed. From the investigation on this delay in development of *L. bostrychophila* eggs as a mechanism of resistance, Nayak et al. [27] discovered that the most successful strategy to control resistant *L bostrychophila* is to apply relatively low concentrations of phosphine for extended exposure times that allow all eggs to hatch to the much less tolerant nymph stage.

Ethyl Formate

Ethyl formate (EF) is being investigated as an alternative to phosphine and methyl bromide for the fumigation of stored products. The compound has been found to have a rapid action against stored product insects and shows promise as a fast-acting toxicant [11]. Unlike phosphine which takes days to kill insects, EF kills target insects rapidly. Field trials have shown that EF has good potential as a fumigant in unsealed farm bins. Residues disappear without aeration by degrading to non-poisonous, naturally occurring products (formic acid and ethanol) [10]. Sealed jar fumigation experiments showed that treatment time and temperature significantly affected the fumigation effects of EF on *L. bostrychophila* adults. Within 24 h of treatment, EF showed a fairly high fumigation activity. Fumigation at 16℃ expressed a even better result than at 31℃. The LC_{50} s of *L. bostrychophila* adults fumigated by EF with an exposure time of 12, 24, 36, 48 and 60 h were 15.882, 15.676, 14.011, 13.154 and 10.495 μL/L, respectively. Fumigation at 20, 25 and 30℃ with a treatment time of 24 h indicated the LC_{50}s of 11.372, 13.283 and 15.676 μL/L, respectively [12]. The investigation on the fumigation activities of EF against *L. bostrychophila* in simulated storehouses with wheat, maize and paddy showed that fumigation activities of EF in the wheat storehouse were the best, followed by the maize warehouse, and then the paddy storehouse. Besides, EF can control *L. bostrychophila* effectively [13].

Essential Oils

Natural plant extracts are commonly used in many developing countries to control insect pests in storage because of economic conditions on small farms [28]. The use of plant extracts, including allelochemical compounds such as essential oils, is a feasible alternative to the use of synthetic insecticides [29]. The activities of natural plant extracts are manifold, and they induce fumigant and topical toxicity as well as antifeedant or repellent effects [29]. Six plant essential oils (extracted from the leaves of six source plants: *Citrus tangerina* Tanaka, *Citrus aurantium* L., *Citrus bergamia* Risso et Poiteau, *Pinus sylvestris* L., *Cupressus funebris* Endl., and *Eucalyptus citriodora* Hook) as repellent and fumigant against *L. bostrychophila* were assessed in the laboratory. The repellency test indicated that *L. bostrychophila* adults were repelled by filter paper strips treated with six essential oils. Of these essential oils, the *C. funebris* oil was most effective followed by that of *P. sylvestris*, *C. tangerina*, *C. bergamia* and *E. citriodora*. The average repellency of the *C. aurantium* oil against *L. bostrychophila* adults was significantly lower than other five test oils by day 14. These essential oils had a high level of toxicity in the fumigation assay against *L. bostrychophila* adults at both 10 and 20 ppm (v/v) [30].

Controlled Atmospheres Studies on Psocids

Controlled atmospheres (CA) are alternative treatments to the use of methyl bromide for post-harvest insect control. The insecticidal properties of CAs have been generally classified into two main types: (a) low oxygen and (b) CO_2 enriched atmospheres. The efficiency of CA, with elevated carbon dioxide, low oxygen levels, or a combination of both, for stored-product insect control has been confirmed by various laboratory and field studies, and several studies on the acute lethal response of psocids to CA have also been reported [3,20].

Although CA possess non-toxic and environmentally benign materials, several researchers have revealed that stored products pests are capable of adapting to these two stresses, resulting in the resistance development to hypoxia or hypercarbia [20]. In the last decade, a series of experiments about CA effects on psocids have been carried out in Chongqing Key Laboratory of Entomology & Pest Control Engineering, China [6,14,15,20,25,31,32]. In the laboratory, *L. bostrychophila* developed and reproduced successfully under CA exposures, but the development and reproduction of *L. bostrychophila* were inhibited by CA exposures. Egg development was more sensitive to high CO_2 than low O_2 concentration due to relatively low respiration rate of the egg stage. Leong and Ho [3] reported that when eggs of *L. entomophila* were exposed to hypercarbia for 24 h, the development of egg was delayed. Although no delays in nymphal development times were observed after hatching, the adult emergence of *L. entomophila* was inversely related to the CO_2 concentration to which the eggs were exposed.

Temperature is one of the most important factors affecting the development and reproduction of psocids [6] and also modifying the effect of CA [3]. Some studies reveal that the influence of CA on the mortality of *L. bostrychophila* is highly correlated to temperature. Similarly, the acute lethal effect of CA in relation to temperature on *L. bostrychophila* was also reported by Bell *et al.* [33]. Under CA exposures, the preoviposition period of *L. bostrychophila* was prolonged and the adult longevity and fecundity were reduced.

The effects of CA and dichlorvos (DDVP) on population growth and resistance development by *L. bostrychophila* indicated that the population of the psocid increased rapidly under natural conditions; after 11 weeks, this population had increased 48.1-fold at 28.8℃, 80% relative humidity. Exposure to CA (35% CO_2, 1% O_2) or DDVP (0.3 mg/mL) alone failed to control the population growth. However, alternating exposure to CA and DDVP provided a significant increase in mortality as compared to those exposed to only CA or DDVP. The results of bioassay showed that both populations exposed only to CA and DDVP developed a low but significant resistance to CA and DDVP, respectively. Probit analysis did not show an appreciable increase in slope value of either population in spite of continuous exposures, indicating considerable heterogeneity of these psocids in response to CA or DDVP and suggesting a greater potential for the development of higher levels of resistance. It is suggested that alternating CA with insecticides could be an important management measure for psocids in storage [15].

Conclusions

There is no single replacement for all the uses of methyl bromide. Each insect problem will require its own solution, mainly revolving around integrated pest management. The most promising alternative fumigants are currently phosphine and EF for psocid control. Although alternatives to methyl bromide are often more expensive and labor intensive, they are practical and do not deplete the ozone layer.

Despite numerous reports of resistance to many insecticides, chemical control will continue to play an important role in psocids control programs. Studies on population ecology and resistance development to control treatments are fundamental to the development Integrated Pest Management (IPM) strategies for psocids.

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