THE LONG JUMP FROM CHEMICAL TO NON-CHEMICAL CONTROL IN STORED PRODUCT PROTECTION: WHICH ARE THE VIABLE ALTERNATIVES TO NEUROTOXIC INSECTICIDES IN THIS META-PESTICIDE ERA?

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ABSTRACT

Currently, stored product protection is based chiefly on the use of chemicals which are, in majority, neurotoxic to insects. However, the continuous use of these substances meets with several drawbacks, such as the high mammalian toxicity of some active ingredients, the detection of residues in the final product, and the development of resistance by several major stored product insect species. At the same time, the increased consumers' demand for residue-free food, the strict requirements of organic food production, and environmental concerns, constitute the future of many active ingredients uncertain. In this context, several alternatives have been evaluated and proposed, based on the use of bio-rational approaches, which do not contain conventional insecticides. On the other hand, despite the fact that there are numerous alternatives to pesticides in stored product protection, there is still inadequate information on their viability for wide scale applications. Nevertheless, there are methods that can be used with success for this purpose, and can, either in part or completely, replace chemicals. Modified and controlled atmospheres are classified among the most promising alternatives to chemical control, since they can be applied in various commodities and at various environmental conditions. Both methods are based on the reduction of oxygen around the treated commodity, to a level that is usually lower than 3 %, causing hypoxia or anoxia. Other techniques are based on the use of macro- or micro-biological control: these include predators, parasitoids and insect pathogens, which are introduced in the facility. Extreme temperatures, known as "heat treatment" or "cold treatment" are also good viable alternatives to aerial insecticides and aerosols in storage and food processing facilities. In the case of heat, ideally, the temperature has to be raised at 50 ^{o}C in all locations of a given facility, while in the case of cold, all insects usually die in 1-2 days at -17.8 ^{o}C (0 ^{o}F). Other methods include the application of natural resource-based inert materials, such as diatomaceous earths, the use of mating disruption and the utilization of mechanical methods in buildings and commodities that have to do with "insect proof food packaging" or "insect proof buildings". All these techniques are now used in large-scale applications, clearly suggesting that the meta-pesticide era in stored product protection is feasible. This feasibility, apart from the insecticidal efficacy, is also related to the fact that the cost of most of these approaches and techniques is directly comparable with the cost of conventional methods that are currently in use.

Key words: stored product protection, non-chemical control, biorational pest management

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IZVLEČEK

DOLG SKOK OD KEMIČNEGA DO NEKEMIČNEGA ZATIRANJA SKLADIŠČNIH ŠKODLJIVCEV: KATERE SO UČINKOVITE ALTERNATIVE NEVROTOKSIČNIM INSEKTICIDOM V OBDOBJU PO INTENZIVNI UPORABI FITOFARMACEVTSKIH SREDSTEV?

Varstvo uskladiščenih pridelkov pred škodljivci je večinoma vezano na uporabo kemičnih snovi, ki na škodljive žuželke (te predstavljajo najpomembnejšo skupino skladiščnih škodljivcev) delujejo predvsem kot živčni strupi. Slaba stran dolgotrajne rabe takšnih snovi je visoka strupenost za sesalce pri nekaterih aktivnih snoveh, pojavljanje ostankov v skladiščenem materialu in njegovih proizvodih ter pojav odpornosti na insecticide pri nekaterih najpomembnejših vrstah skladiščnih škodljivcev. Hkrati pa naraščajoče zahteve potrošnikov po hrani brez ostankov fitofarmacevtskih sredstev, stroge zahteve ekološke pridelave in splošna skrb za okolje vplivajo na to, da je prihodnja uporaba številnih aktivnih snovi precej negotova. V tej zvezi je bilo doslej preučevanih veliko okoljsko sprejemljivih načinov, ki ne vsebujejo sintetičnih insekticidov in nekateri med njimi se danes že uporabljajo v praksi. Na drugi strani pa se, kljub dejstvu, da je znanih veliko alternativnih načinov za zatiranje skladiščnih škodljivcev, še vedno srečujemo z njihovo nezadostno uporabo v velikih skladiščnih prostorih. Vseeno so že znani alternativni načini, ki se z uspehom uporabljajo v širši praksi in ki že delno ali v popolnosti nadomeščajo kemične snovi. Spremenjena ali nadzorovana atmosfera se uvršča med najbolj obetajoče alternative kemičnim pripravkom, saj se lahko uporablja v različnih skladiščnih materialih in v različnih okoljih. Obe metodi temeljita na zmanjšanju koncentracije kisika v skladišču na manj kot 3 %, s čimer pri žuželkah pride do hipoksije (pomanjkanje kisika v tkivih) ali anoksije (odsotnost ali hudo pomanjkanje kisika v tkivih). Ostali načini temeljijo na uporabi makro- in mikrobiotičnih agensov, in sicer plenilcev, parazitoidov in žuželčjih patogenov, ki se znašajo v skladišča. Tudi uporaba ekstremne temperature, znana kot “vroče tretiranje” ali “hladno tretiranje”, predstavlja dobro alternativo kemičnim fumigantom v skladiščih in živilskih obratih. V primeru vročine, je najbolj učinkovito, da temperaturo v celotnem skladišču povišamo na 50 °C, pri mrazu pa je znano, da žuželke pri -17,8 °C navadno poginejo po enem do dveh dneh. Druge alternativne načine predstavljajo naravni inertni materiali, kakršen je na primer diatomejska zemlja, metoda zbeganja in mehanični načini zatiranja skladiščnih škodljivcev, s katerimi se škodljivcem fizično prepreči dostop v prostor ali v pakirno enoto. Omenjeni načini se danes že uporabljajo v široki praksi, kar nakazuje na to, da je mogoče skladiščne škodljivce učinkovito zatirati tudi brez kemičnih sredstev za varstvo rastlin. To dejstvo potrjuje tudi cena omenjenih alternativnih načinov, ki je primerljiva s ceno klasičnih (kemičnih) načinov zatiranja skladiščnih škodljivcev.

Ključne besede: varstvo uskladiščenih pridelkov, nekemično zatiranje, bioracionalno varstvo rastlin

1 BACKGROUND

Control of stored product insects is heavily relied on the use of chemicals, such as fumigants and residual insecticides. Conversely, terms such as “biological control” or “alternative control methods” have a different meaning in stored product protection, in comparison with field pests. For example, the addition of pathogens in the final or the pre-final commodity to control insects, should be always balanced with the consumers’ perception and their willingness to accept “pathogen-treated” products. At the same time, predators and parasitoids that are added in storage facilities to control other insect species should be also regarded

under the prism of the possible increase of insect fragments or insect-related contaminants. The term "alternative" is even more complicated in stored product protection. In the case of field pests, often alternatives to pesticides are reduced-risk techniques or even novel formulations that are safe for mammals even during application. In the stored product ecosystem, many alternatives are generally toxic to mammals, if there is a direct exposure. For example, nitrogen or carbon dioxide may also endanger human health, if there is exposure during the application. Another paradigm is extreme temperatures, i.e. cold and heat, which can also cause problems if there is some certain level of exposure, while, in some occasions, can also harm the commodity and the equipment of the area that they are applied.
Phillips and Throne (2010) introduced the term "biorational approaches" in stored product protection. This term sets the scene for the techniques that are successful and viable alternatives to traditional pesticides and have low risk if used properly. Those methods should be in compliance with international trade and also with regulatory guidelines. At the same time, they have to satisfy the increasing demands for organic food production, and minimize any negative impacts on food. In the following, some of these approaches are presented.

2 BULKED COMMODITIES

With this term we refer mainly on cereal grains, but most of the techniques that are to be mentioned here can be also applicable for other types of products, such as legumes, herbs or dried fruit. Grains are usually either fumigated or directly sprayed with residual insecticides, which are expected to protect the commodity from the insects as long as the insecticidal substrate retains its insecticidal efficacy. Traditionally, aeration in silos has been used for decades for four main purposes: insect control, mould prevention, maintaining seed viability and reduction of grain moisture (Navarro and Noyes, 2002a). Cooling is also another way to apply air on the grain, in order to drastically reduce insect development. The aim of this method is to cool down the grain mass 12-14 ^{o}C or even lower (Navarro and Noyes, 2002b, 1994, Arthur and Casada, 2005, 2010). Decision on either aeration or cooling, depends of various factors, i.e. environmental conditions, grain moisture etc. Despite the fact that aeration and/or cooling usually takes place in the less warm periods of the year, summer aeration is feasible (Arthur *et al*., 1998, 2010, Navarro and Noyes, 2002a).
Ozone has been successfully evaluated in grain bins and, apart from its effect on insects, it is also very effective for microbial control (Mason *et al*., 1997, McDonouch *et al*., 2011a, b, Isikber and Athanassiou, 2015). In fact, McDonouch *et al*. (2011a, b) developed a screw conveyor that allowed better mixing of the grain with the ozone gas, allowing better penetration in the grain mass and providing higher efficacy. Several other gases, such as nitrogen, can be successfully used on bulked grains for insect control. The main goal of this application is the reduction of the oxygen level to less than 3 %, and, in some cases, less than 1 %. The idea of nitrogen application is simple: given that nitrogen corresponds to approx. 78 % of the air, the technique is based on the use of nitrogen generators that force nitrogen to enter in the area that is to be applied. Recently, large nitrogen generators have been successfully evaluated for insect control in concrete silos with barley in Cyprus (Navarro *et al*., 2012).
There are certain insecticides that are now registered as alternatives to traditional neurotoxic grain protectants. One promising category of alternative insecticides is diatomaceous earths, which are dusts based on phytoplanktons, called diatoms. Diatomaceous earths can be applied directly on the product with the same technology with traditional grain protectants, does not affect the properties of the final product and they are non-toxic to mammals (Athanassiou *et*

al., 2003, 2005). Other contact insecticides that are registered for this purpose in many parts of the world and have low mammalian toxicity include the insect growth regulator S-methoprene and the bacterial metabolite-based insecticide spinosad (Athanassiou *et al*., 2010, Hertlein *et al*., 2011). Those insecticides have been proved effective for a wide range of insect species, particularly beetles and moths.

3 FOOD PROCESSING FACILITIES

Manipulation of temperatures in a storage facility is currently widely used in many parts of the world, in many different types of facilities and commodities. Heating a processing facility at 50 ^oC can rapidly kill all insects and life stages (Mahroof *et al*., 2003, Roesli *et al*., 2003). Heat can be also used to control hidden infestations which cannot be easily controlled with other methods. Usually, heat is applied on the facility (i.e. a flour mill or a pasta factory), where usually there are regulatory restrictions regarding the application of insecticides. However, heat can be also applied on the commodity. For example, Khamis *et al*. (2011a, b) found that the application of heat through catalytic infrared radiation was able to control internal-feeding insects within the grain kernels. Cold treatment has been also tested for commodities with good results. Flinn *et al*. (2015) found that, in flour bags, the application of -17.8 ^oC (=0 ^oF) controlled successfully all insect life stages, including eggs. Cold treatment may be more applicable for disinfecting commodities, particularly organic product, rather than buildings and facilities.

One of the most promising technique for the control of moths indoors is mating disruption, which is based on the deployment of dispensers that contain high loading levels of (*Z,E*)-9,12-tetradecadienyl acetate, the male attractant of several stored product moths of the family Pyralidae, known also as ZETA or TDA (Trematerra *et al*., 2011, 2013, Trematerra, 2012). This artificial pheromone covers the pheromone that is produced by the females, so females cannot be located by males. Earlier studies show that mating disruption can work in several types of commodities and facilities in Europe, at different climatic conditions and target species (Sieminska *et al*., 2009, Trematerra *et al*., 2011). This method can be also used for beetles (Mahroof and Phillips, 2014). A similar technique, known as auto-dissemination of pheromones or auto-confusion, has been successfully applied in storage and processing facilities in Italy and Greece (Trematerra *et al*., 2013). This technique uses baiting stations that contain ZETA along with electrostatically charged dust, in order to infect males with the female pheromone, which is then transmitted among individuals through "pseydo-mating". This method is expected to be used commercially in the next years for insecticide dissemination at the post-harvest stages of agricultural products.

4 META-PESTICIDE ERA IN STORED PRODUCT PROTECTION

These were only some examples of "real world" alternatives to traditional pesticides that are currently in use in large scale insect management. Apparently, before any insecticidal application, sanitation is the first step in every strategy regarding stored product protection. The phase out of methyl bromide, which was dominant until recently in several post-harvest systems, made essential the evaluation of "greener" substances and methods that can be utilized as substitutes. Today, and despite the fact that chemical control is still dominant, non-chemical methods become more spread and adopted, probably in a wider extent than the adoption of non-chemical control in field crops. The withdrawal of several substances, along with the increased demands and rules for regulatory and food safety, made stored product protection a pioneer area in non-chemical control, much more than other areas of crop protection.

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