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Advances and non-chemical alternatives for the management of insect pests of stored grains

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Abstract

The target of production and productivity of various crops is increasing day by day and in order to achieve this target, losses including the post-harvest ones are to be managed and reduced. Developing countries faces more post-harvest losses than the developed ones due to many reasons (economical, psychological, technology, faith etc.). In order to achieve this target, we have to control insect-pests, throughout the food supply chain including their safe storage. For the management/control of stored grain insect-pests, synthetic insecticides are used in almost all countries, however, their undiscriminating use has resulted into many thoughtful problems including resistance of pest species and residues in food grains used for human consumption. Methyl bromide and aluminium phosphide are the two most frequently used synthetic chemicals as fumigants for stored grain protection, however, most of the countries have phased out them due to depletion of ozone layer and insect-pest control failures. Due to long and over use of phosphine, many insect-pests have gained resistance/tolerance to its fumigation in most of the countries. Due to all these concerns and also, keeping in view the growing demand for healthy, clean, organically produced, and residue free food, it is essential to find appropriate replacements to the use of chemical pesticides. In this article, we have reviewed certain advances and non-chemical alternatives for the management/control of wide range of stored grains insect pests and their products.

Keywords: stored grain, insect-pests, management, eco-friendly, advances

Introduction

Annual grain loss due to pests (mainly insects and microbials) in developing nations are projected to be between 500 million US dollars and 1 billion US dollars (Campbell *et al*., 2004) [16]. Since 1960s, liquid and gaseous pesticides have been widely used to control stored-product pests in various storage facilities like granaries, mills, warehouses etc. (White and Leesch, 1996) [72]. Organophosphates, carbamates, and pyrethroids have gradually replaced chlorinated insecticides during the last 50 years. They are normally applied during loading and come in the form of liquids or powders. They are made to provide long-term protection against insects which are harmful for the produce (Arthur, 1994) [6]. Synthetic pesticides are used in a variety of countries to manage pests and rogue insects and have proven to be effective. It is the most popular and most effective control measure which is practiced by farmers and even by seed storage companies. Organophosphates viz. pirimphos-methyl malathion, and chlorpyrifos-methyl (White and Leesch, 1996; Tomlin, 2000) [72, 69], pyrethroids viz. cypermethrin and deltamethrin (Ribeiro *et al*., 2003) [60], and carbamates viz. carbaryl, carbofuran (Ogah. and Coker, 2012) [49], for residual control, they are applied directly to the grain. The most widely used compounds in underdeveloped countries are methyl bromide (MB) and phosphine. Regardless of their efficiency, synthetic pesticides have drawbacks like high prices, genetic resistance, health risks from toxic residues, and contamination/pollution in the environment. (Mehta and Kumar, 2020a) [34]. Surface sprays of bags as and when the insect-pests are visible, are done with insecticides such as malathion, primiphos-methyl, DDVP, fenitrothion etc. As a result, pesticide resistance is a common flaw associated to the widespread usage of these chemicals in numerous locations. (Zettler and Cuperus, 1990; Collins *et al*., 1993; Odeyemi *et al*., 2010; Throne *et al*., 2000) [78, 18, 48, 66].

In many regions of the world, stored grain pests have developed resistance to malathion, pirimiphos-methyl, cypermethrin and many more insecticides (Ribeiro *et al*., 2003) [60]. Furthermore, international trade has speeded up the spread and dispersal of resistant insect strains in stored goods. In Canada, insect pest resistant to malathion got incorporated mostly through foreign trade, according to White and Leesch (1996) [72]. Similar situation, along with many more insecticides has occurred in different countries such as the United States as reported by Zettler (1974) [78] and Beeman and Nanis (1986) [10], in Iran as reported by Javadzadeh *et al.* (2017) [27], in Nigeria by Odeyemi *et al.*, (2010) [48], and in Egypt as reported by Toppozada *et al.*, (1969) [70]. Because of ozone depletion potential, the EPA (2001) [22] proposed phasing out of methyl bromide use and its production by 2005. In addition, few to many stored-product insect-pests have developed mild to severe resistance against methyl bromide and phosphine, the two most famous fumigants (Champ and Dyte, 1977; Subramanyam and Hagstrum, 1995) [17, 65]. These issues have underlined the necessity for new sorts/alternatives of insect-control to be developed and administered accordingly. Thus, in this article, we have tried to cover eco-friendly and new alternatives to synthetic and harmful chemicals which can be a part of management of insect-pests of stored grains either solely or in integration.

1. General/mandatory steps necessary for good storage

a) Sanitation and handling of grains

- Keeping a check for leakage of rain water and proper drainage facilities
- Removal of any type of foreign material from healthy grains
- Assessment of capacity
- Avoiding hooks on storage bags
- Different storage structures should be far from the ventilators or doors
- Moisture content should be according to the recommended ones
- Use of modified and latest storage structures
- Threshing floor should be clean, free from insect infestation, away from vicinity of village.
- Harvesting machines, threshing machines and means of transport should be cleaned before use
- Closing of rat burrow with broken glass pieces and mud.

b) Proper stacking of grains

- Bags stacking should be done on wooden dunnage, 0.5 meter away from the wall of storehouse
- Spacing between rows should be 2 to 3 meters
- More than 15 bags is not recommended and 1/5th space of total storage from the roof should be left.

c) During storage

- Clean and disinfest empty used gunny bags by dipping in boiled water and drying under sun.
- Proper aeration whenever necessary
- Proper check after a long period of rain
- Ensuring disposal
- Emergency arrangement for discrimination, rescue and processing, whenever any type of damage takes place due to any reason
- Treat walls with hot water splash using any type of cleaner and keep ventilators and doors open for sun drying and aeration

2. Non chemical alternatives for the control/ management of insect-pest of stored grains

1) Legal method

The Plant Quarantine Order (2003) and the Destructive Insects and Pests Act (1914) govern the guidelines or restriction of insect movement through goods into the country and between different districts within the same country. The Food Corporation of India was founded on January 14, 1965, with its initial district office in Thanjavur, Tamil Nadu's rice bowl, and its headquarters in Delhi. (https://fci.gov.in/):

1. Farmers' interests are protected by effective price support activities.
2. Food-grain distribution for the Public Distribution System across the country
3. Maintaining adequate operational and buffer food grain inventories to maintain national food security
4. Regulate market prices so that customers can buy food grains at a consistent price.
5. To pay farmers a fair price for their produce.
6. To make food grains affordable to all members of society, particularly the most vulnerable.
7. Maintaining buffer reserves as a means of ensuring food security
8. To act in the market to maintain price stability

It is one of India's largest enterprises, and Asia's largest supply chain management company (second in world). It has five zonal offices and twenty-four regional offices. The purchases are done from farmers at the rates set by the Indian government. MSP stands for Minimum Support Price. There are no volume restrictions on procurement; any quantity can be purchased.

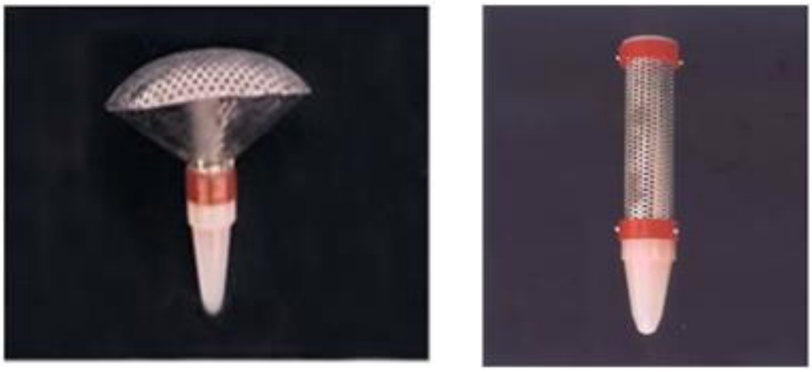
2) Grain protection devices

These devices are used for mass trapping and monitoring of insect pests of stored grains, thus serving the purpose of their management (Fig 1). The latest used devices are TNAU insect probe trap (Mohan, 2007; Athanase 2012) [41, 8], against *Rhyzopertha dominica*, *Sitophilus cryzae* and *Tribolium castaneum*), Pitfall trap ((Mohan and Raghavan, 2008; Mohan and Rajesh, 2016a) [43, 42], against insects active on upper surface of grains, TNAU TWO-IN-ONE MODEL TRAP (Mohan and Rajesh, 2016b) [44], against pulse beetle, Indicator device (Mohan, 2007; Mohan and Rajesh, 2016b) [41, 44], against insect-pest of stored pulses, TNAU Insect Removal Bin (Mohan, 2000; Mohan and Rajesh, 2016b) [39, 44], against rice weevil, red flour beetle, lesser grain borer, saw toothed beetle, UV light Trap for insect godowns (Mohan *et al.*, 2016a; Rajesh *et al.*, 2016) [43, 59], against lesser grain borer, red flour beetle, psocids and saw-toothed beetle, Hand and Machine operated Egg removal device (Divya and Mohan, 2002; Mohan, 2005; Athanase, 2012; Mohan and Rajesh, 2016b) [21, 40, 8, 44], against pulse beetles. For properly using the above-mentioned devices, “hands on training kit” has been made, which is popularly known as TNAU-Stored Grain Insect Pest Management Kit (Mohan, 2007; Mohan and Rajesh, 2016a) [41, 42]. Another device is the Electrically conductive roller mill. For infection in stored food grains, this widget employs the fundamental principles of electrical physical phenomenon and compressive force. One kernel operates as a electrical device during a single kernel characterization system with 2 resistors and a voltage–divider circuit. The voltage throughout the crushing of kernels between the rolls is employed to see the electrical phenomenon of the kernels. The insects inside the kernel leads to an increase in the moisture level of the kernel, making it easier to distinguish sound kernels from infested kernels. Insect eggs, young larvae, and dead insects cannot be detected with this approach in grains having low moisture content (Pearson and Brabec, 2007) [55]. Furthermore, because this method analyses a single kernel at a time, the time required is extremely significant. Pearson *et al*., (2003) [54] designed an electrically conductive roller mill for wheat categorization called the "insect-o-graph". On the basis of the system's signal characteristics and the conductance signal received, infested kernels were distinguished from uninfested kernels. Pearson and Brabec (2017) [13] evaluated 1 kg of wheat in roughly 2 minutes and found contaminated kernels in excess of 70%, as well as *R. dominica* larvae and pupae. Major internally infesting insects, rice weevil (*S. oryzae*) and lesser grain borer (*R. dominica*), were tested. It is a useful tool for grain classification at receiving stations since it gives grain storage managers the information, they need to decide whether a bin should be fumigated/treated or discarded (Figure 3). The usage of SPME is another method. Different volatiles were released by larvae and adults, and these volatiles were valuable for early infestation monitoring. Methods for detection of insect infestation and determining grain quality are becoming more widespread. Furthermore, this technology aids in early infestation identification, storage age determination, and food grain varietal distinction, among other things. SPME employs headspace techniques to isolate volatile molecules evaporated from samples, which are subsequently condensed and analysed using GC-MS for volatile quantification. Extraction time and temperature affect the efficiency and sensitivity of the SPME process. The collection of more analytes is aided by a high temperature and long extraction period (Laopongsit *et al*., 2014) [31]. Senthilkumar *et al*., (2012) [63] used headspace analysis and GCMS to identify *T. castaneum* and *C. ferrugineus*. Niu *et al*., (2016) [46] employed SPME in conjunction with gas chromatography-flame ionisation detection and GC-MS to determine connections between grain quality and storage time, as well as grain quality and *R. dominica* insect infestation in wheat. By using SPME clenched with gas chromatography-mass spectrometry, Abuelnnor *et al*., (2010) [1] detected different volatile components from infested wheat flour and wheat grain with the *T. confusum* and *S. granaries*, respectively (Figure 3). Last but not least, E NOSE is gaining favour for the control of stored grain insect pests. This approach, also known as smell detection, involves detecting and identifying odours generated by insects, such as pheromones. Insect pheromones regulate insect behaviour and aid in the transmission of messages across large distances between insects (Wilson, 1963) [74]. By identifying the volatile components, this method was commonly utilised to detect infestation or contamination during storage (Olsson *et al*., 2002; Paolesse *et al*., 2006) [50, 51]. E-nose has the capability to spot insects in stored grains quickly and mechanically (Zhang *et al*., 2007) [80]. The employment of varied electronic nose device varieties and instruments is predicated on the electronic fragrance detection principle (Wilson, 2012) [73]. Associate in Nursing odour device set, a knowledge pre-processor, and a knowledge interpretation system form up the E-nose. The volatile chemicals contained in the headspace of stored food grains are detected by the sensor set, which reacts by changing the electrical characteristics. It has a built-in database that allows it to distinguish between different volatiles. To attain the desired results, particular care must be taken while choosing a sensor array for specific volatile organic chemicals. The sensing element array ought to be chosen to maximise the instrument's overall performance and supply distinct property profiles for every application (Phaisangittisagul *et al*., 2010) [56]. Evans *et al*., (2000) [23] used e-nose to differentiate between plagued and non-infested samples of various fungous species through the event of secondary volatile metabolites, while, Wu *et al*., (2013) [75] used E-nose to discriminate and sight insect infestations, differentiate between insect species, and predicted insect population with some success. The odour detection method has a moderate sensitivity and excellent accuracy, as well as a low operational cost.

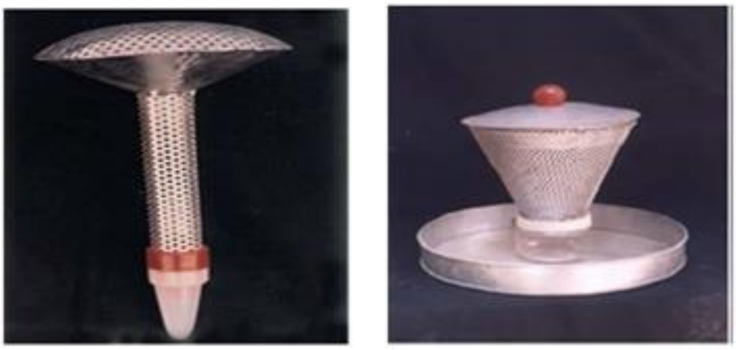
3) Irradiation

It is the process of using electromagnetic radiation of specific wavelengths and energy to control pests on a commodity (grain or product). Ionizing radiation comes from radioisotopes like cesium and cobalt. Insect disinfestation of stored grain, pulses, and products has been demonstrated to be effective with low dose applications (less than 1kg). (Lan *et al*., 1987) [30] calculated the minimal dose of Gray required to kill *Sitophilus zeamais* and *Callosobruchus maculatus* on or inside the grains without impacting viability, hence rendering the grains free of infestation for laboratory research. They infected maize and cowpea seeds for 52 days each, then separated the cultures into 50g in 42 plastic containers. The seeds were subsequently irradiated with dosages of 40, 80, 150 200, 300 and 500 Gy [Gray], in a Co-60 gamma cell. The number of insects surviving in each case was counted, as well as the effect of the gamma irradiation on the viability of the grains. Both *S. zeamais* and *C. maculatus* were found vulnerable to gamma doses ranging from 200 to 500 Gy. At some doses, the mortality rate for both insects was as high as 100%. At doses below 1kGy, gamma irradiation was found to have no effect on seed viability. This was most likely due to increased insect eating, which damaged the seed germ and resulted in poor germination of seeds. However, due of reduced feeding, doses exceeding 80Gy resulted in increased seed germination. Hallman (2018) [24] revealed that a small amount of doses, ranging from 0.05 kGy for *Tenebrio molitor* to 0.45 kGy for *Sitotroga cereallela*, were effective in preventing the reproduction of stored product pests. In today's globe, little but growing volumes of different grains are being irradiated, particularly in Asia. Irradiation of some stored commodities is permitted in at 33 nations, with 14 countries allowing it for all products. Irradiation may offer an advantage over other treatments in reducing viability of weed seeds, which is an area of Phyto sanitation of stored products/seeds.

Infected barley grains were irradiated with a GUR-120 unit at doses ranging from 150 Gray (Gy)–1000 Gray (Gy), as well as a "Duet" electron accelerator at doses ranging from 200–1000 Gy (@100 Gy/imp.). After 15 days, they determined that gamma irradiating saw-toothed grain beetles (imago stage) at doses ranging from 170 to 1000 Gy (@ 100 Gy/h) and 150 to 600 Gy (@ 1800 Gy/h) resulted in 100% pest mortality. After irradiation, the death rate of saw-toothed grain beetles was depending on the dose and irradiation rate. The pest died 15 days, 9 days, and 6 days after being exposed to 250 Gy, 400–550 Gy (at a dose rate of 100 Gy/h), and 900–1400 Gy (at a dose rate of 1800 Gy/h). However, at 1200 Gy, 100% pest death was seen. The ionising region of the electromagnetic spectrum is made up of visible light and shorter wavelengths. Visible light only ionises a few molecules, such as chlorophyll, which is ionised to begin photosynthesis. The use of ionising UV light as a grain surface treatment and to control pests in stored commodities has been investigated Phillips and Throne (2010) [66] and raised three problems against irradiation of stored product: 1) Safety issues of radioisotopes to general public; 2) The myth that radiated food gathers radioactive substances and becomes radioactive and 3) Importing countries and the general public have no tolerance for insects in the food or needful items. Because these concerns are primarily based on perceptions, the answers are primarily educational. Concerns about radioactive isotopes are unfounded; food irradiation facilities are well quipped and protected, and the employment of machine sources i.e. e-beam and X-ray completely eliminates any risk provided by radioactive isotopes.

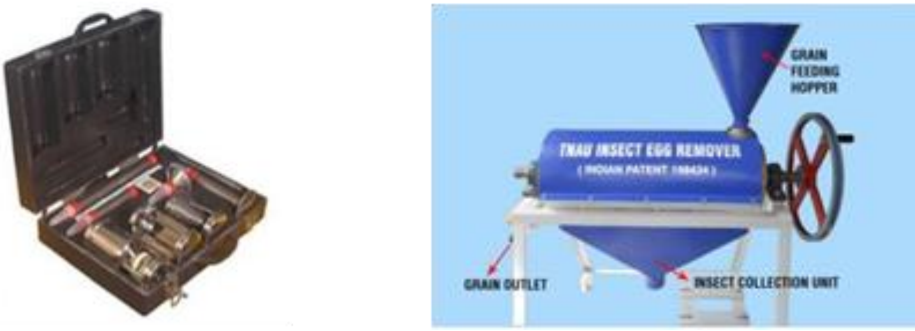


Pitfall Trap Insect Probe Trap



Two-in- One Model Trap Indicator Device

TNAU Insect Removal Bin UV light Trap



TNAU-Stored Grain Insect Pest Management Kit Egg removal device

Fig 1: Grain protection device

4) Biological control

Parasites and predators are either generalists or specialists, depending on the nutritional ecology. Generalists eat a wide range of species that are biochemically unrelated to one another, whereas specialists eat only a few species. In storage godowns, biological control isn't very promising. Some predators and parasites, on the other hand, have been observed to affect several stored grain pests. Few predators are more widely used to manage insect pests in storehouses, such as the hemipteran bug *Xylocoris flavipes* (Reuter) and a few other anthocorid bugs. In warehouses, these hemipteran insects have the ability to manage Coleopteran and Lepidopteran insects. *Tribolium casteneum, Tribolium confusum, C. pusillus, R. dominica*, and *T. granarium* are all predatory bugs, while *X. flavipes* is one of the most studied biological control agents among predatory bugs (Ahmed 1991) [3]. In stored chickpea, *Dorylus labiatus* is the most effective predatory ant, killing 84.64 and 98.26 percent of *C. chinensis* larvae and pupae, respectively. *Monomorium minimum*, which is a predatory ant, was discovered to be very effective egg predator, with an egg mortality rate of 84.85 percent. (Aslam *et al*., 2006) [7]. Rahman *et al*., (2004) [58] revealed that, *X. flavipes* killed more *C. pusillus* larvae in a jar full of wheat kernel than *T. confusum* and *T. castaneum* larvae. Females have been found to be more predatory than males. *C. cephalonica* moth emergence was greatly reduced by inoculating rice with *X. flavipes* and *Blaptostethus pallescens* at a rate of 30 nymphs/10kg of rice (Anon. 2010) [5]. *Bracon hebetor* of family Braconidae and *Venturia canescens* of family Ichneumonidae are two common parasitoids employed to control *E. cautella* numbers. *B. hebetor* could kill 93.4 percent of *Corcyra Cephalonica* larvae if released (Patel *et al*., 1982) [52], and *B. hebetor* activity in *Corcyra* rearing rooms was seen all year (except April) in Gujarat (Dabhi, 2010) [19]. *Trichogramma pretiosum*, an egg parasitoid, and *B. hebetor*, a larval parasitoid, were shown to be successful in lowering Indian meal moth population by 84% and almond moth by 98%, respectively, while *B. hebetor* alone caused a reduction of 97.3 percent. Another parasitoid that successfully controls dermestid larvae is *Laeluis pedatus* (Say) (Bethylidae). The egg parasitoid *Trissolcus basalis* (Hymenoptera: Scelionidae) responds to synomones emitted by herbaceous plant plants which are induced by feeding and oviposition activity of the bug *Nezara viridula* (L.) (Heteroptera: Pentatomidae). Damaged leaves of broad bean (*Vicia faba* L.) containing eggs of *N. viridula* is known to produce synomones which attracted *T. basalis* (Colazza *et al*., 2004) [81]. Insect pests of stored grains are reported to be suppressed by some nematodes. Laznik and Trdan (2010) [32] investigated the effectiveness of three strains of *S. feltiae* against *S. oryzae*. The study was carried out at different concentrations and different temperatures and they discovered that all of the strains were most effective at 25 °C and that their effectiveness was directly proportional to the concentration.

Advantages of Biocontrol

- Minimal toxic risks to farmers, storekeepers and consumers
- It can be used on organic grain
- Reduced risks to the environment
- Fits readily in to an integrated pest management program
- No resistance development
- Able to find out pests which are usually inaccessible to many other methods.

5) Ozonation

Ozone is an allotropic powerful oxidant and reduces/inhibits mold, spore development and can kill stored product insect-pests, thus, serving as a non-chemical alternative for stored grain protection. C. F. Schonbein, a European scholar, was the first to identify ozone in 1839. It was initially commercially utilised in 1907 in the treatment of municipal water supplies in Nice, then in 1910 in St. Petersburg (Kogelschatz, 1988) [28]. Photochemical smog, which is produced by UV. lamps, high-voltage electric arcs, and gamma radiation plants. It is formed in the stratosphere and can be detected in photochemical smog (Mustafa, 1990) [45]. Ozone decomposes quickly at room temperature and does not build significantly in the absence of continuous ozone production (Miller *et al*., 1978) [38]. At room temperature, ozone is nearly colourless with a pungent and distinctive odour similar to "fresh air after a thunderstorm". A diatomic oxygen molecule must split to make ozone, and the ensuing free radical oxygen is then free to react with another diatomic oxygen molecule to form a tri-atomic ozone molecule. However, a large level of energy is required to break the O–O bond. To manufacture ozone, ultraviolet radiation (with a wavelength of 188 nm) and corona discharge procedures can be utilised to commence free radical oxygen production (Rice *et al*., 1981) [61]. The corona discharge approach, on the other hand, is commonly employed for ozone creation in commercial settings. Ozone coating of grain has two distinct phases. Section one is characterised by speedy degradation of the gas and slow movement through the grain. In Phase 2, gas flows freely through the grain with very little degradation and happens once the molecular sites accountable for gas degradation become saturated. The speed of saturation depends on the rate of the ozone/air stream. The concentration of fifty ppm gas for 3 days ends up in 92–100% mortality of adults of red flour beetle, *T. castaneum, S. zeamais* and *P. interpunctella* and conjointly reduced contamination level of the plant life *Aspergillus parasiticus* by sixty-three per cent on the kernel surface. The enticing facet of gas is that it decomposes apace (half-life of 20–50 min) to molecular O while not deed a residue and tested as a good technology for grain protection, while not moving its end-use quality (Pawar *et al*., 2015) [53]. Bonjour *et al*., (2011) [12] tested hard red winter wheat in steel bins containing 13,600 kg. One bin was given ozone treatment, while the other was used as a control. Insect-pests were placed in bins and exposed to different ozone concentrations (0, 25, 50, and 70) parts per million by volume for 1, 2, 3, and 4 days in sampling tubes (ppmv). In the case of *P. interpunctella*, ozone treatments were only effective on pupae, but after two days of treatment, 100 percent death of adults of S. oryzae was seen at all dosages. After, four days of treatment, ozone treatment killed all *T. castenium* (adults) at 50 and 70 ppmv, but all treatments failed to kill *R. dominica*, *Cryptolestes ferrugineus*, and *O. surinamensis*. Each cylinder had 55 kg of hard red winter wheat and after one day of exposure, they found that a concentration of 70 ppmv was. effective against female of *Liposcelis bostrychophila* Badonnel and *L. paeta* Pearman. It was, however, ineffective against the eggs of these two species.

Advantages

- Residue less food grains

- Broad spectrum
- Marked as safe for use in food processing by FDA
- Alternative against resistant insects
- Easy generation
- Does not affect the quality of grain
- No chemical hazards or artificial disasters associated

6) Nanotechnology

Nano is a Greek term that translates to "dwarf" (0.1- 100 nm). Nanotechnology is the synthesis and application of materials, devices. and systems at the nanometric scale by controlling their properties and structure. Electrically charged nanoparticles exhibit a dipole-dipole interaction that favours aggregation formation while resisting dissociation pressures. Nanomaterial aggregates adhere securely to the body surfaces of insects with electric charges. Water loss becomes irreversible once the protective wax coating is disturbed, resulting in dehydration and death by sorption and abrasion. Silver nanoparticles ($AgNO_3$) Silica (diatomaceous earth, synthetic silica (SiO_2), sands, and Silica Aerogel), Aluminium oxide (Al_2O_3), Zinc oxide (ZnO), Copper oxide (Cu_2O), Titanium dioxide (TiO_2) are some of the nanocides utilised (Ragaei and Sabry 2014) [57].

Zahir *et al*., (2012) [82] used aqueous leaf extracts of *Euphorbia prostrata* as an eco-friendly green material to produce silver nanoparticles (Ag NPs). They tested the efficacy of aqueous *E. prostrata* leaf extracts, silver nitrate ($AgNO_3$) solution (1mM) and generated Ag NPs against the adults of *S. oryzae*. UV-visible spectroscopy, X-ray diffraction, Fourier transform infrared spectroscopy, and scanning electron microscope examination were used to characterise the produced nanoparticles. The nanoparticles were rod-shaped and were of the size 25 to 80 nano meters, with an average size of 52.4 nano meters. Aqueous extract, $AgNO_3$ solution, and manufactured Ag NPs had LD_{50} values of 213.32, 247.90, and 44.69 mg/kg, respectively; LD_{90} values of 1648.08, 2675.13, and 168.28 mg/kg. These findings show that aqueous extracts of *E. prostrata* leaves, as well as manufactured Ag NPs, can be effectively used as eco-friendly strategy for controlling *S. oryzae* and this was probably the first report on the effectiveness of synthesized nanoparticles.

7) Host resistance

The study of resistance to pests of stored grain poses a major challenge to plant breeding because the grain does not give any signal through biochemical compounds to trigger defense mechanisms. The environmental storage conditions might also interfere with the selection process as these conditions influence the pest's developmental rate and, consequently, might mask resistance. Like the pests of major field crops, the pests of stored grain are also subjected to the same resistance mechanisms such as antixenosis, antibiosis, and tolerance. Stored grain insect pests require sustenance and shelter, but may show less preference for a particular grain due to colour, shape, and other factors, this is known as antixenosis. Antibiosis occurs when insects usually feed on a given grain that causes adverse effects on their biology due to the presence of toxins, growth inhibitors, and deficiency in a nutritional element while, tolerance is the ability of seed to raise plant even after fed by stored pest (Singh 2013) [64]. A major component of an integrated pest management strategy is the use of host plant resistance to reduce losses and minimize the impact on grain quality. For example, identification of QTL associated with maize weevil resistance in maize will enable breeders to exploit the genetic variation and increase the efficiency in delivering maize varieties resistant to the weevil (García-Lara *et al*., 2009) [83]. With the advancements in science, a lot of varieties have been developed showing resistance to insect-pests. Nowadays, some genetically modified (transgenic) plants are also available that carry genes for insect resistance.

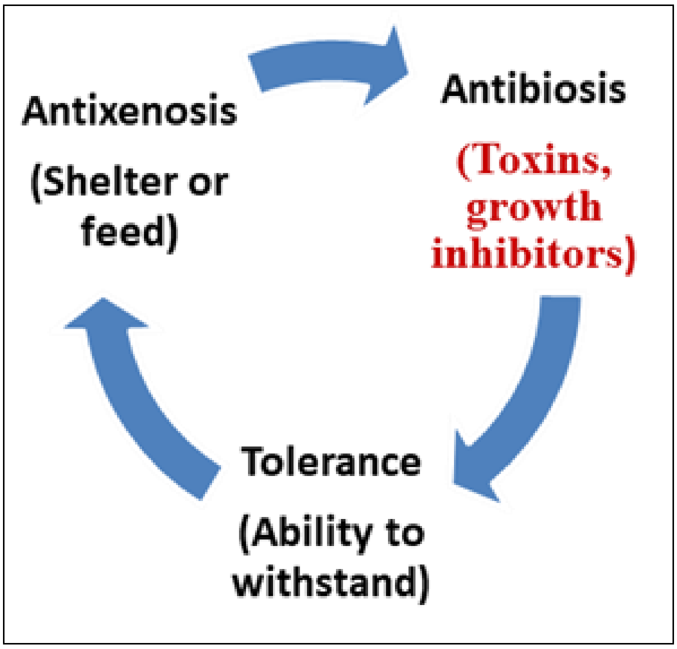


Fig 2: Types of insect pest resistance (Singh, 2013)

The most important prerequisite for generating insect-pest resistant varieties is to discover resistant sources by screening available germplasm (Mehta and Kumar, 2020b) [35]. Studying the biology of the pest and some effective control measures that do not contaminate the environment are also prerequisites (Mehta and Kumar, 2021) [36]. Knowledge of the mechanisms and factors that contribute to insect resistance in host plants is useful in determining appropriate selection criteria and breeding procedures for improving insect-pest resistance in cultivars of a given crop. In the same way biochemical, physiological, genetical and histological characters of plant may possibly be associated with insect pest resistance and should be studied (Mehta *et al*., 2021) [37].

Yoza *et al*., (2015) [77] discovered that avidin rice was resistant to both *T. confusum* and *S. cerealella.* This result was expected because avidin corn is resistant to both of these stored-product bugs (Kramer *et al*., 2000) [29]. When compared to Bt endotoxins' insecticidal action, which is generally limited to lepidopterous pests, avidin's insecticidal activity against both coleopterans and lepidopterans is a significant advantage.

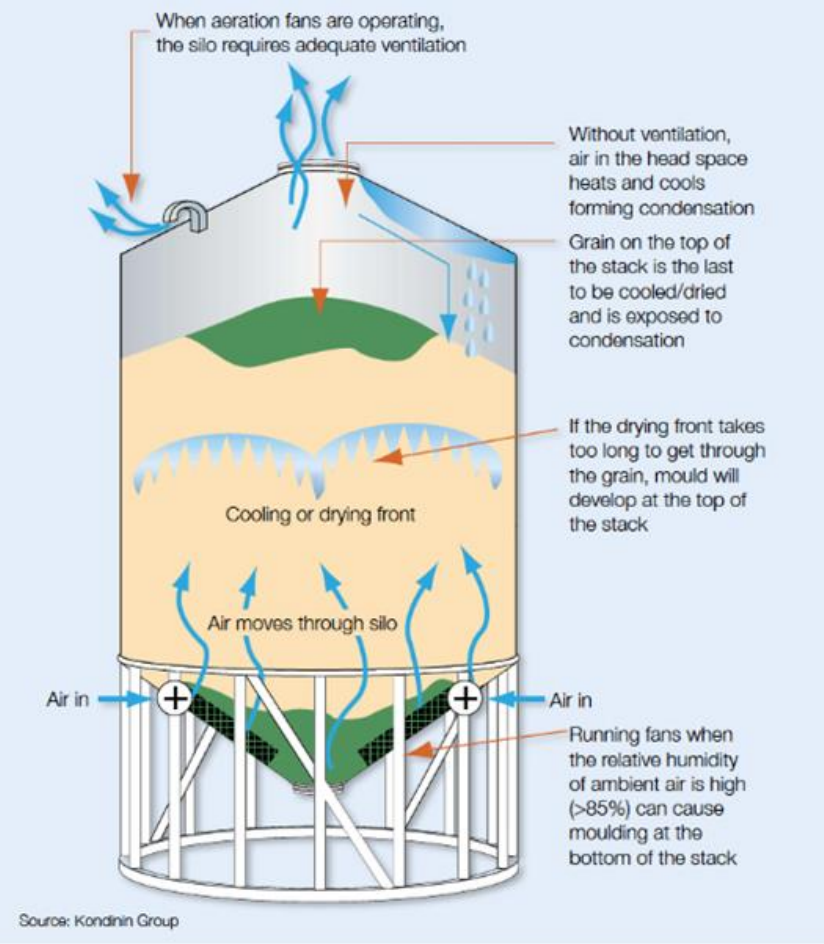
8) Microbial control

This control mechanism is rarely used. *Bacillus thuringiensis* produces Bt toxins, which are the most potent types. Certain botanicals are used with *B. thuringensis* for more effective control. *Beauveria bassiana*,, *Lecanicillium lecanii*,, *Metarhizium anisopliae*,, *Paecilomyces farinosus*, and *Plodia interpunctella* granulosis virus (GV) are used to control Indian meal moth and saw-toothed grain beetles, while *B. thuringienesis* protein Cry IC is used to kill diamond backmoth (Buda and Peckjulyte, 2008; Throne and Lord, 2004) [14, 67]. *M. anisopliae* conidia in combination with dust carriers, result in increased adult mortality of *T. castaneum* in stored wheat and a reduction in grain damage (Batta and Safiah, 2005) [9]. According to Samodra *et al*., (2006) [62], *B. bassiana* formed in kaolin caused the most *S. oryzae* death and the weight loss was least in rice, followed by talc and tapioca flour under storage conditions. The first and second instar larvae of the larger grain borer, Prostephanus truncates, were more sensitive to B. bassiana in stored maize than the third instar, with the pupal stage being substantially more susceptible than the other stages, according to Dhuyo *et al*., (2007) [20]. McGaughey *et al*., (1978) [33] observed good control (92 per cent) of *P. interpunctella* and *E. cautella* in bulk wheat and maize by treating the surface layers with dust or aqueous suspension of *B. thuringiensis*. Ahmedani *et al*., (2008) [4] investigated three commercial *B. thurinsiensis* formulations against *T. castaneum* and discovered that Ecotech Pro outperformed Dipel ES and Bactospeine in controlling the pest. *E. cautella* has been found to have a nuclear polyhedrosis and a granulosis virus. *P. interpunctella* is infected by both viruses, however the granulosis virus from *P. interpunctella* did not cause any negative effect to *E. cautella* (Hunter *et al*., 1973) [25]. *C. cephalonica* has produced yet another nuclear polyhedrosis virus. Young larvae were shown to be the most vulnerable in all cases. Broad bean beetle is controlled by the fungus *B. bassiana*, *M. anisopliae,* and *V. lecanii*, which act as bioinsecticides. Nigella and mustard oils not only inhibited oviposition but also had a negative impact on fecundity. *B. bassiana* and *M. anisopliae* fungi provided the best protection against *Bruchus rufimanus* infestation in the field. Bioinsecticide treatments resulted in a much-decreased percentage of grain damage and seed weight loss. Under normal conditions, the red flour beetle, which is a major pest of stored and processed grains, is resistant of *B. bassiana* (Balsamo) Vuillemin. In the instance of the red flour beetle, *B. bassiana* had a higher efficacy when the moisture level was lower. The fungus' efficacy was boosted by the desiccating conditions (Toews *et al*., 2005) [68]. In addition, a mite species known as *Phaseolus vulgaris* is employed to inhibit stored goods (Jan *et al*., 2006) [26].

9) Aeration systems

By modifying biological activity and lowering grain quality losses, forced/artificial aeration of stored grains is one of the most effective and is receiving attention as a non-chemical strategy for controlling insect pests of stored grains. Aeration should be chosen based on air properties that prevent or restrict the growth of harmful organisms. Grain managers can benefit from automatic aeration system controllers because they are one of the most cost-effective solutions available. When the temperature drops to unfavourable levels for insect eating, growth, and reproduction at night, aeration systems should be turned on immediately after binning. Aeration airflow is often measured in CFM/bu i.e. cubic feet of air per minute per bushel grain. Light aeration systems (0.1 CFM/bu or less) are best suited to cooler areas because they require extensive operation times to reduce grain temperatures. Aeration systems for medium and fast grain (0.2 CFM/bu to 0.8 CFM/bu) are used on a regular basis to lower grain temperature and equalise temperatures in stored grains. After just a few nights of operation, grain temperature will be equal to nighttime air temperature. A minimum of 0.2 CFM/bu is suggested in Oklahoma. 1 CFM/bu or more is required for high-speed grain cooling (Figure 2).

Natural air grain drying, which demands high-speed airflows more than 1 CFM/bu, should not be mistaken with grain cooling. Wet grain is placed in a bin for natural air grain drying, and the fan is turned on constantly for several weeks, until the grain has dried to a safe moisture level. Grain cooling entails a period of fan operation to cool the grain, followed by periodic operation to keep the grain mass at consistent temperatures. The airflow rate should be determined by the intended application of the aeration system. A mild aeration system may be chosen if grain will be stored with a safe moisture content and the aeration system will be utilised to avoid moisture migration. Grain temperature must be strictly managed and a quick aeration system is preferable when storage with moisture contents one or two percent above permissible moisture levels is attempted. In general, a quicker airflow should be utilised if grain needs to be cooled quickly. Aside from these, aeration time, airflow direction, fan selection, and aeration costs are all important factors (Noyes *et al*., 2002) [47].



Source: Kondinin Group

Fig 3: Air movement within an aerated silo

10) Flexible fumigation chambers with external fans

Effectiveness of a gas distribution strategy that uses external fans positioned outside the chamber in a series of commercial fumigations to inhibit narcissus fly larvae in bulbs for export. The concept is to exploit the elasticity of the PVC liner to create air flow (Fig 3). This is performed by directing airflow along the walls of the liner, causing internal turbulence and mixing the air with the fumigant within the chamber. By positioning fans opposing the bubble's corners, it was possible to divide the airflow along all sides of the bubble wall. The fumigant was mixed by recirculation during the 4-hour fumigation interval, and the amounts of methyl bromide were compared to previous results. In 1–1.5 hours, external fans combined with flexible PVC chambers allowed for even gas dispersion throughout the chambers, however recirculation did not allow for even distribution for the whole 4-hour fumigation duration. The death rate of narcissus fly larvae after fumigation was 100 per cent. The idea is to use the elasticity of the PVC liner to create air movement. This is accomplished by directing airflow along the liner's walls, resulting in a ripple type motion that causes internal turbulence, mixing the air properly with the fumigant within the chamber. The following findings were discovered:

a) Even distribution (with fans): It took 1-1.5 hours to distribute evenly.

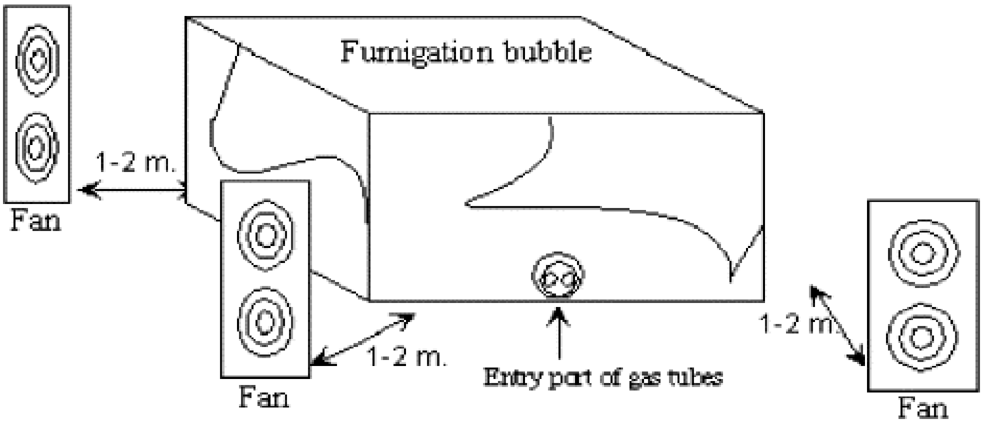
b) Even distribution (without fans): until 4 hours no even distribution was found.

External fans are used to produce turbulence within the bubble of fumigation, resulting in a even fumigant concentrations in a short period of time. This approach is not only effective for fumigating narcissus bulbs, but it may also be used to fumigate other commodities in bubbles. A non-toxic and environmentally friendly fumigant could be used instead of a toxic or hazardous fumigant. The pest control operator's skill is needed to determine where the external fans should be set to produce the most effective ripple effect on the PVC chamber walls. (Fig 3).

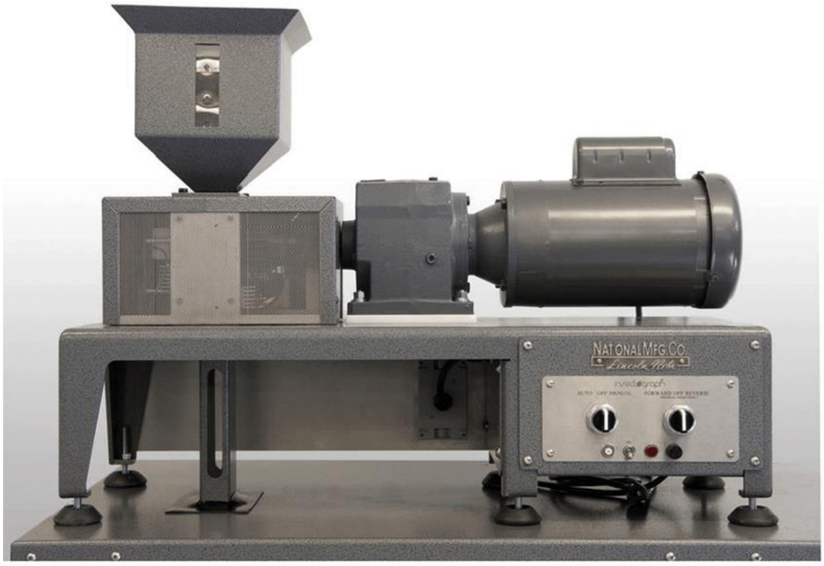
11) Microwave technology

Microwave disinfestation appears to hold a lot of promise as a new way to destroy insects in stored grains (Vadivambal *et al*., 2010) [71]. Continuous or pulsed operation is possible with microwave generators. It leaves no chemical residues and maintains grain quality. Feasibility of using microwave radiation to control stored insects attacking wheat as a non-toxic alternative to chemical pesticide fumigation. Microwave radiation influence on the chemical composition of grains and insect biochemical features were also investigated. *T. castaneum*, a red rust flour beetle, *C. maculatus*, a cowpea beetle, and *S. granarius*, a wheat weevil, were subjected to varying levels of microwave power during 10, 20, 30, 40, 50, and 60 seconds. On wheat grains and wheat flour, 100 per cent mortality of *T. castaneum*, *S. granarius*, and *C. maculatus* adults was observed at a power level of 60 seconds, 40% at a power level of 40 seconds, and 60% at a power level of 50 seconds, respectively. When cowpea grains were exposed to microwave radiation at 40 and 80 per cent power levels during 10, 30, and 60 seconds, the physical and chemical features of the grains changed, as compared to untreated healthy and infested grains. When the power level and exposure duration were increased, the moisture content, total protein, and total carbs in treated wheat grains, wheat flour, and cowpea grains dropped, but the temperature increased. The physiological impacts and biochemical characteristics of the above-mentioned insects were different when treated at low power levels of 20% and 40% and exposure times of 10 and 30 seconds. In *T. castaeum* and *S. granarius*, total protein content dropped when compared to the control, but total carbs and total lipids increased. Surprisingly, total carbs increased in *C. maculates* while total lipids dropped, and AchE activity in all exposed flies decreased when compared to untreated insects.

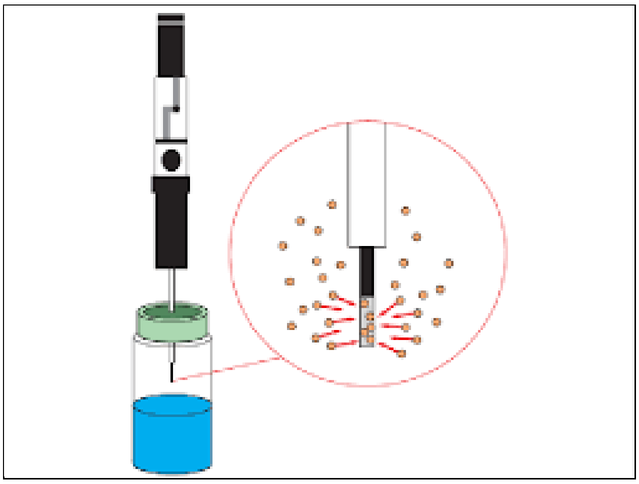
T. castaneum, C. ferrugineus, and *S. granarius*, three typical stored-grain insects, were tested on wheat, barley, and rye using a pilot-scale commercial microwave dryer operating at 2.45 GHz. At 14, 16, and 18 percent moisture content, stored-grain insects attacked 50-gram grain samples (wet basis). The samples were then microwaved at four different power levels for 28 and 56 seconds: 200, 300, 400, and 500 W. In barley and wheat, 100 percent mortality was attained in adults of all three species when exposed for 28 seconds at 500 W and 56 seconds at 400 W. Adults of *T. castaneum* and *S. granarius* were completely killed in rye at 400 W (28 s) and 300 W (56 s), respectively, but *C. ferrugineus* was completely killed at 500 W (28 s) and 400 W (56 s) (56 s). *T. castaneum* eggs were the most vulnerable of the wheat-feeding *T. castaneum* life stages, followed by larvae, pupae, and adults. In barley and rye, *T. castaneum* eggs were the most fragile of all life stages, while adults were the least vulnerable, with no discernible difference between pupae and larvae. The quality of barley and barley malt treated at 400 W for 56 seconds was significantly worse than the quality of barley and barley malt treated at 500 W for 28 seconds. There was no significant difference in quality between microwave-treated rye and control wheat, save for a decrease in flour yield. At 500 W and 28 s exposure time, the moisture loss equivalent to 100 percent mortality in barley, rye, and wheat was 1.9, 2.5, and 2.0 percentage points, respectively, in barley, rye, and wheat. The grain will be treated in layers because to the limited penetration. One of the major problems with microwave heating is the non-uniform temperature distribution. Researchers tried to develop a microwave heating model that could predict temperature distribution in microwave-heated food (Yang and Gunasekaran, 2004; Campanone and Zaritzky, 2005) [76, 15]. Microwave drying done incorrectly is known to result in a low-quality product (Adu and Otten, 1996) [2]. Wheat grain endosperm structure was significantly altered after being microwaved for more than 90 seconds (64 °C). When the microwave treatment time is extended, the damage increases (Blaszczak *et al*., 2002) [11]. Another difficulty with microwave heating is the large number of variables that affect microwave heat transfer behaviour, such as food thickness, shape, and dielectric properties.



a)



b)



c)

Fig 4: a) Flexible fumigation chamber with. external fans; b) Electrically conductive roller mill; c) SPME

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