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Assessment of microwave energy for disinfestation of grain

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Abstract. Infestation of grain by insects is widely controlled by the use of insecticides. Use of contact insecticides results in chemical residues left in the food which may have adverse effects on humans. Also insects develop resistance to both contact insecticides and fumigants. Microwave disinfestation offers an alternate way to disinfest grain. Microwaves are electromagnetic waves with frequencies ranging from 300 MHz to 300 GHz. The use of microwaves for killing insects is based on the dielectric heating of insects present in grain, which is a relatively poor conductor of electricity. There is a possibility of selective heating of insects in grain because of a significant difference in dielectric constants between grain and insects. The major advantage of using microwave energy is that no chemical residues are left in the food and insects are unlikely to develop resistance to this treatment. Principle of microwave disinfestation, experimental results from previous studies and the advantages of using microwaves for disinfestation of grain are discussed.

Keywords: microwave, disinfestation, electromagnetic spectrum, radio waves, dielectric heating, dielectric constant.

INTRODUCTION

Annual losses of grain due to insects and rodents have been estimated to be around 10% in North America and 30% in Africa and Asia (Hill 1990, cited by White 1995). Economic losses due to insects and microorganisms in grain have been estimated to be around one billion dollars per year in the United States (Brader et al. 2000). Insects associated with raw grain and processed food cause quantitative and qualitative losses which result in decreased nutritional value, reduced seed germination and lower economic value. Insect infestations can occur just prior to harvest, during storage in a variety of structures such as cribs and metal or concrete bins, and in-transit in a variety of carriers. Stored-product insects often are found in farms, warehouses, and food handling facilities. Therefore, preventing economic losses caused by stored-product insects is important from the field to the consumer's table (Subramanyam and Hagstrum 2000).

Harvested crops are stored on-farm or in commercial grain handling facilities, like primary and terminal elevators. In Canada, grain is mainly stored on-farm (Sode et al., 1995). Maintaining quality and quantity are the main criteria for safe storage. Canada has a legally defined zero tolerance for pest insects in stored grain for human consumption. If a stored-product insect is detected in a wheat sample, the grain is termed infested and the grain is recommended for treatment to kill the insects (Canada Grain Act 1975).

Successful control of various insect species with chemical insecticides has contributed substantially to the ability of modern agriculture to provide abundant supplies of high-quality food. Chemical control methods are essential for efficient production and preservation of food products. For the past several years, efforts have been devoted to study possible alternative insect control methods that might be helpful in minimizing the environmental hazards associated with chemical insecticides (Nelson and Stetson 1974). Microwaves and radiofrequency energy can be used to control insects in stored cereals and cereal products.

The objectives of this paper were:

1. To present an overview of the various insect control methods.
2. To review the literature related to microwave disinfestation of grain.
3. To determine whether microwave disinfestation of grain can serve as an alternative to chemical methods of disinfestation.

METHODS OF INSECT CONTROL

The various methods of insect control are: physical, chemical and biological. The implementation of an insect-control program requires a thorough appreciation of all the elements of an infestation problem: the insects; their age, species and distribution; their survival and developmental rates under different environmental conditions; and the various chemical and non-chemical methods available.

Physical methods

Insects in stored grain can be controlled by manipulating the physical environment or applying physical treatments to the grain and insects. Physical methods to control insects include different types of traps (probe traps, pheromone traps) manipulation of physical environment (Sinha and Watters 1985), mechanical impact, physical removal, abrasive and inert dusts and ionizing radiation (Muir and Fields 2001). The physical variables that are usually manipulated are temperature, relative humidity or grain moisture content, and relative composition of atmospheric gases in the intergranular air. Low temperatures are usually obtained by aeration with cool ambient air. Methods to obtain high grain temperatures are more diverse, including: microwaves, infrared, hot air and dielectric heating. Controlled atmosphere techniques involve changing the carbon dioxide, oxygen and nitrogen content of storage atmospheres to render them lethal to insects (Banks and Fields 1995). Physical control methods tend to be slow and some may not give high levels of mortality even when well managed. They can be used where the infestation is low. Microwave disinfestation is a physical method to control insects in stored-grain.

Chemical methods

Pesticides are among the most commonly used chemicals in the world, and among the most dangerous to human health. Currently over 2.5 million tonnes of such chemicals, worth over 30 billion US dollars, are applied to crops in the world (Gannage 2000). The chemicals used to control insects in the bulk stored-grains and cereal processing industries comprise two classes namely contact insecticides and fumigants. Contact insecticides kill insects which contact treated surfaces or air particles. Some of the commonly used insecticides are malathion, pirimiphos-methyl, chlorpyrifos (Sinha and Watters 1985). Fumigants are gaseous insecticides applied to control insects in grains and processed foods that are inaccessible by contact insecticide. Some of the commonly used fumigants are methyl bromide and phosphine (Sinha and Watters 1985). Methyl bromide is involved in the depletion of the atmospheric ozone layer. Hence it has been banned effective 2005 in developed countries, except for quarantine purposes (Fields and White 2002). Many alternatives have been tested as replacements for methyl bromide, from physical control methods such as heat, cold and sanitation to fumigant replacements such as phosphine, sulfuryl fluoride and carbonyl sulfide.

Drawbacks of chemical control methods A major limiting factor for using insecticide is that insects have developed resistance to insecticides. A world-wide survey of stored-product insects revealed that 87% of 505 strains of the red flour beetle, *Tribolium castaneum*, collected from 78 countries were resistant to malathion (Sinha and Watters 1985). In several countries where malathion resistance is a severe problem, other control methods such as alternative insecticides, fumigants or physical control methods have to be substituted. Even though insecticide and fumigants are applied with care and in limited quantity, there is a possibility of these chemicals remaining in the food grains and having adverse effects on the humans. The World Health Organization estimates that 0.2 million people, mainly farmers die every year worldwide from pesticide poisoning. Pesticide exposure also may cause health hazards from acute problems such as skin rashes and asthma attacks, to chronic problems such as emphysema and cancer (Gannage 2000). Chemicals also have a hazardous effect on the environment. Phosphine is increasingly used as a treatment to replace methyl bromide but the major drawback with phosphine is the rapid increase in insect resistance to this compound (Taylor 1994; Fields and White 2002).

Biological methods

There are many approaches to biological control of pests in stored products, including the use of predatory insects and mites, parasitoids and pathogens. Unlike chemicals that need to be applied to a wide area, natural enemies can be released at a single location and they find and attack the pests in a grain mass. There are no chemicals involved and these methods do not pose serious risk to the consumers or to the environment. But the biological method also has some disadvantages.

Drawbacks of biological control methods Biological control agents are usually species specific. Since most infestation comprise multiple species, several different isolates or species of biological control agents may be needed. Biological control methods act slowly and consequently much damage may occur before control is effective. It is not usually suitable for dealing with heavy infestations (Subramanyam and Hagstrum 2000). Currently, little expertise or infrastructure exists to supply control agents or support the use of biological control methods.

MICROWAVE DISINFESTATION

Properties of microwaves

Microwaves are electromagnetic waves with frequencies ranging from about 300 MHz to 300 GHz and corresponding wavelength from 1 to 0.001 m (Decareau 1985). Microwaves are invisible waves of energy that travel at the speed of light, 3×10^8 m/s. In the electromagnetic spectrum, microwaves lie between radio frequencies and infrared radiation (Fig. 1). From the broad range of microwave frequencies available, a few are designated for industrial, scientific and medical applications (ISM). As a result, utilization of specific microwave frequencies comes under the regulations of the federal communications commission (Copson 1962). For all practical purposes industrial applications are carried out at 915 MHz in the USA, 896 MHz in the UK and 2450 MHz worldwide (Mullin 1995).

Principle of microwave heating

Microwave heating is based on the transformation of alternating electromagnetic field energy into thermal energy by affecting polar molecules of a material. All matter is made up of atoms and molecules and some of these molecules are electrically neutral but many are bipolar. When an electric field is applied the bipolar molecules tend to behave like microscopic magnets and attempt to align themselves with the field. When the electrical field is changing millions of times per second (915 or 2450 million times per second), these molecular magnets are unable to keep up the forces acting to slow them. This resistance to the rapid movement of the bipolar molecules creates friction and results in heat dissipation in the material exposed to the microwave radiation (Brygidyr 1976). Biological material placed in such radiation absorbs an amount of energy which depends on the electrical characteristics of the material and heat is produced. In general, the higher the moisture and oil content the more energy is absorbed and the more heat is generated.

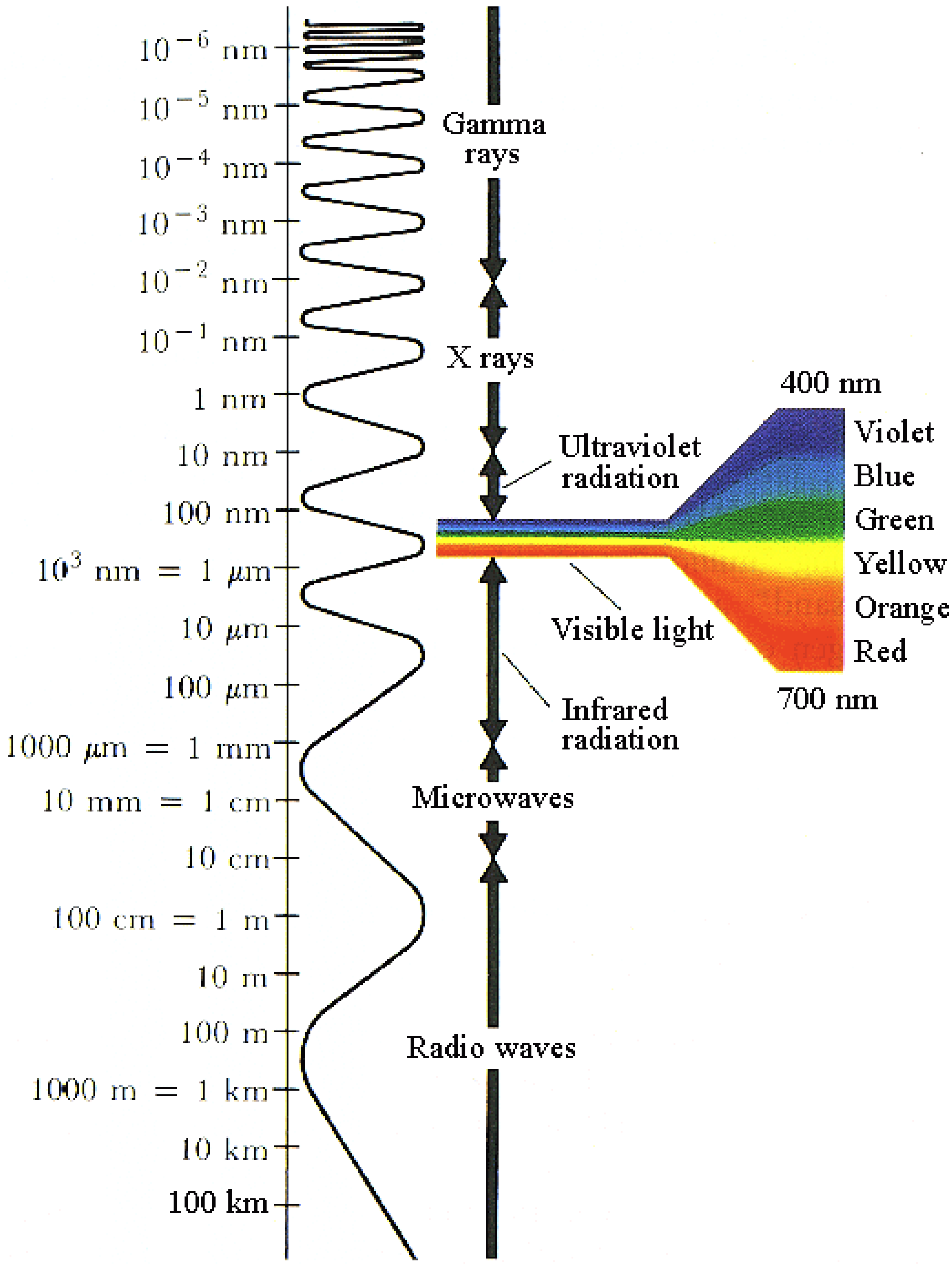

Fig 1: Electromagnetic spectrum
(Source: Comins and Kaufmann 2005)

Principle of microwave disinfestation

The use of microwaves for killing insects is based on the dielectric heating effect produced in grain, which is a relatively poor conductor of electricity. Since this heating depends upon the electrical properties of the material, there is a possibility of advantageous selective heating in mixtures of different substances (Hamid et al. 1968; Nelson 1972). In a mixture of dry food stuffs and insects, it is possible to heat the insects to a lethal temperature because they have high moisture content while leaving the drier foodstuff unaffected or slightly warm (Hurlock et al. 1979). Insects that infest grain, cereal products, seed and other stored products can be controlled through dielectric heating by microwave or lower radio frequency energy. Raising the temperature of infested materials by any means can be used to control insects if the infested product can tolerate the temperature levels that are necessary to kill the insects.

Advantages of disinfestation using microwave energy

The major advantage of using microwave energy is that no chemical residues are left in the food and hence no adverse effects on human beings (Hurlock et al.1979). Microwave energy has no adverse effect on the environment as in chemical methods. Insects are unlikely to develop resistance to this treatment (Watters 1976). High frequency radiation may not only kill insects by the dielectric heat induced within them but may also affect the reproduction of any survivors (Hamid et al. 1968).

CASE STUDY 1

Hamid et al. (1968) presented a method for detection and control of insects in samples of wheat and flour. Experiments were conducted for measuring the scattering coefficients, dielectric constant, and loss tangent of wheat and flour at 10 GHz. These results were used in the design of equipment for testing penetration of microwaves and mortality of insects at 2.45 GHz. The penetration and mortality tests were conducted in a screened room with microwave absorbing material placed such as to absorb power not dissipated in the sample. Exposure tests were conducted on three common pests of stored grain namely *Tribolium confusum, Sitophilus granarius* and *Cryptolestes ferrugineus*. The required exposure times for 90% mortality of the three species in wheat were approximately 30, 30 and 18 s, respectively. The corresponding exposure time for 90% mortality of *T. confusum* in wheat flour was 37 s.

For the penetration test the sample taken was a cubic foot of wheat with 10.5% moisture content. Since this illumination technique yielded approximately 0.114 m (4.5 inches) of penetration, it was concluded that circulation of bulk wheat in a properly designed wave guide would appear to be a superior method. They concluded that bulk heating is not feasible when the depth is greater than 0.101 m (4 inches). However, if wheat is illuminated in thin layers on a conveyor belt, then a satisfactory mortality of insects can be achieved in a reasonable time and at a reasonable cost.

CASE STUDY 2

Hamid and Boulanger (1969) presented a method for the control of *Tribolium confusum* by microwave heating. The method was based on the detection of dielectric properties of the insect and the design of microwave apparatus of sufficient capacity to disinfest reasonable quantities of grain by selective dielectric heating. Samples of insects were scattered in small plastic containers filled with wheat and allowed to pass through the wave guide. Temperature measurements were made inside the container of bulk wheat. For *T. confusum*, 70% mortality was obtained when the grain temperature was 55^{o}C and 100 % at 65^{o}C.

Quality tests of treated wheat

To determine the effects of high frequency radiation on the milling and baking qualities of wheat, three samples were heated to 55, 65, and 80^{o}C and compared with control samples. There was no effect on the milling quality or protein content of the wheat. But the bread making quality was affected deleteriously and progressively, as the treatment temperature was increased. The loaf volume of the control sample was 550 cc whereas the loaf volume of the samples at 55, 65 and 80^{o}C were 435, 360 and 315 cc respectively. The effects were similar to those produced by improper drying of grain.

CASE STUDY 3

Watters (1976) studied the susceptibility of *Tribolium confusum* to microwave energy operating at 8.5 GHz and 30 W average output power, by irradiating vials of infested wheat. Wheat samples at 8.5, 12.5 and 15.6% moisture content were infested with ten *T. confusum* adults. After irradiation, each block was removed from the radiation source and the wheat sample was allowed to cool to 32^{o}C. The samples were then stored at 27.5^{o}C and 70% relative humidity for 2 d, when mortality was assessed. A set of untreated controls was maintained under the same conditions.

The radiation sensitivity of eggs, larvae and pupae was determined. Ten individuals of each stage were placed in a vial that contained wheat at 16% moisture content. After irradiation periods required to attain temperature of 50, 60 or 75^{o}C, the samples were removed and allowed to cool to 32^{o}C.

After 105 s, wheat at 15.6, 12.5, and 8.5% moisture contents had attained 75, 68, and 51^{o}C respectively. The corresponding mortalities obtained were 100, 90 and 68%. There was higher mortality in insulated than in non-insulated vials. Only 67.8% mortality was obtained when the wheat temperature reached 75^{o}C in non- insulated vials compared with 98% mortality in insulated vials, indicating the value of insulation in sustaining the heating effect. The lower mortalities in the non-insulated vials may be due to high surface area to volume ratio which would contribute to rapid loss of heat during and after irradiation.

Tribolium confusum larvae were more tolerant than eggs or pupae. A maximum temperature of 50^{o}C enabled 82% of the treated larvae to reach the adult stage whereas only 27% of the treated eggs completed development. Complete mortality of eggs and pupae were obtained at 75^{o}C, but 21% of the larvae completed development. This shows that *T. confusum* larvae were more tolerant to the heating effect than eggs or pupae. Throughout all experiments, control mortalities were less than 5%.

CASE STUDY 4

Hurlock et al. (1979) constructed a machine consisting of a tunnel approximately 8 m long of rectangular cross section measuring 152 x 228 cm, through which a variable speed moving belt passed. An 896 MHz generator produced a microwave beam that was made to traverse the belt a number of times over a distance of 3 m before being absorbed in a tank of water. The infested materials were passed through the tunnel in polythene bags on the moving belt. The exposure time could be altered by varying the speed of the belt and generator output. A series of tests was run with a variety of exposure times and power settings and the insects were placed in polythene bags with 200 g of food material. The first tests were conducted on bags of wheat of 13.7% moisture content, containing 50 adult beetles of either *Oryzaephilus surinamensis* (saw-toothed grain beetle), *Tribolium castaneum* (red flour beetle) or *Sitophilus granarius* (granary weevil). Another test was conducted on cocoa crumbs of 18% moisture content containing either ten larvae of Ephestia *cautella (*warehouse moth) or 50 adult red flour beetles.

During examination of the samples, it was noticed that there were more survivors in samples that comprised predominantly powdery material than in those that contained a large proportion of lumps. It, therefore, appears that the fine material offered more protection than the lumpy material. Samples of treated cocoa beans examined in the quality control laboratory showed no change in fat or moisture content. But exposure to microwave radiation progressively lowered the peroxide level indicating that some chemical change was caused in cocoa and that no food should be treated without first ensuring that its quality is not impaired.

CHALLENGES IN MICROWAVE DISINFESTATION

Hamid et al. (1968) concluded that the drawback in microwave disinfestation was the poor penetrating power of microwaves and they have shown that microwave treatment of bulk grain is not feasible when the depth is greater than 0.101 m (4 inches).

Hamid and Boulanger (1969) concluded that bread making quality of wheat is affected by exposure to microwave radiation and suggest that further tests are necessary to determine the fundamental changes in wheat components that lead to the decrease in loaf volume. Macarthur and Appolonia (1979) studied the effects of microwave radiation and storage on hard red spring wheat flour. They examined the physical dough properties and baking characteristics immediately and at definite time intervals after radiation treatment. Analysis of the flour and bread indicated that exposing the flour to high levels of microwave radiation produced an abnormal farinograph curve exhibiting two peaks, whereas low levels produced bread with loaf volumes and overall bread characteristics equal to or better than those of the control flour.

The experiment conducted by Hurlock et al. (1979) showed that some chemical changes occur due to microwave radiation and no food should be treated without first ensuring that its quality is not impaired. Campana et al. (1993) studied the physical, chemical and baking properties of wheat dried with microwave energy. They stated that the protein content was not affected but the functionality of gluten was altered gradually with increasing time of exposure

Nelson and Charity (1972) compared the dielectric properties of different cereals and cereal products at different frequencies and concluded that selective heating of insects in a cereal was less likely to occur at microwave frequencies but it may occur at radio frequencies. The experiments of Baker et al. (1956) also support this conclusion. Nelson and Stetson (1974) studied the dielectric heating treatments of rice weevils in wheat at 39 and 2450 MHz and showed that the lower frequency was much more effective in killing the insects. Thuery (1992) has stated that irradiation at frequencies in excess of 1 GHz has almost no selective effect on insects. Wang et al. (2003) studied the differential heating of insects in dried nuts and fruits at microwave and radio frequencies. They concluded that differential heating of insects in walnuts does occur at 27 MHz but not at 915 MHz.

Cost estimates for microwave and radio frequency insect control is estimated to be around three to five times more expensive than chemical control (Nelson and Stetson 1974). But cost factors change with time and developing technology. A major improvement in the efficiency of the treatment could change the economic picture.

CONCLUSIONS

Based on the results of previous experimental studies, published in the literature, the following conclusions can be drawn:

Disinfestation of grain by microwave power is possible if grain is passed in thin layers on a conveyor belt. When the wheat is exposed to microwave radiation, the bread making quality of wheat is affected at higher temperatures. Various stages of insects have different susceptibility to microwave power and *T. confusum* larvae are more tolerant compared to eggs and pupae. Selective heating of insects does not occur at microwave frequencies but it does occur at lower radio frequencies. If the microwave disinfestation is made economical, it may serve as a safe and effective alternate method of insect control to chemical pesticides.

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