8 Innovative Environmentally Friendly Technologies to Maintain Quality of Durable Agricultural Produce

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CONTENTS

8.1 INTRODUCTION

8.1.1 BACKGROUND AND HISTORY OF POSTHARVEST TECHNOLOGIES

There is an increasing imbalance between the demands of the First World for quality food uncontaminated by insecticidal residues, and the desperate need of Third World populations to maintain and protect their harvested grain from the deprivations of molds and insects so as to maintain a minimum level of food security.

In developed countries, loss of quality is particularly important. Although quantitative losses are generally low, quality is often degraded because of insect infestation or mold activity. Losses of biological origin such as those caused by grain or insect respiration or limited drying due to aeration in storage are common. These losses for cereals, on an annual basis, are usually less than 1%.

In developing countries, poor handling and storage methods under warm and humid climatic conditions promote rapid deterioration of the stored foodstuffs. In those countries, the major portion of grain and pulses (sometimes up to 80% of the national production) is kept on the farms for home consumption. Postharvest losses of food grain in developing countries have been conservatively estimated during the

1980s at 10–15% by the FAO's Special Action Programme for the Prevention of Food Losses. For example, losses of corn due only to insects in farmers' stores in Nigeria, Swaziland, and Kenya were in the order of 6–10%.

Increased public concern over the adverse effects of pesticide residues in food and the environment has led to the partial substitution of use of contact pesticides (typically organophosphates and pyrethroids) and fumigants by alternative control methods. Therefore, nonchemical and environmentally user-friendly methods of pest control in the postharvest sector are becoming increasingly important. It is worth noting that of the 14 fumigants listed some 20 years ago by Bond (1984), only 2 remain today in regular worldwide use, namely, phosphine and methyl bromide (MB). Methyl bromide kills insects relatively quickly, but it will be phased out in developed countries by 2005 and in developing countries by 2015, because of its contribution to stratospheric ozone depletion (UNEP, 2002). Although there are exemptions for quarantine and preshipment purposes, as well as the possibility to apply for exemptions where no alternative exists, the applicant has to demonstrate that every effort is being made to research alternative treatments. In contrast, phosphine remains popular, particularly in developing countries, because it is easier to apply than methyl bromide. However, many insects have developed resistance to phosphine over the last decade.

Grains can be stored for extended periods provided that there is no insect infestation and that their water activity is low enough to prevent microbial growth. However, quantitative or qualitative losses still occur. Qualitative losses, for example, may consist of changes in physical appearance, in nutritional degradation, in loss of germination capacity, in the presence of insects or their fragments, or in contamination by mold or the presence of mycotoxins. Some of these are difficult to detect visually.

If the moisture content is maintained sufficiently low, insects remain the main concern for the quality preservation of durable agricultural commodities. Therefore, in this chapter the major emphasis is placed on innovative friendly technologies addressed to the control of insect pests. Such methods fall into four main groups: A) physically based technologies that can be used to manipulate the storage ecosystem; B) application of phyto-extracts; C) use of pheromones; and D) biological control.

This chapter covers the main areas of progress in the understanding and adoption of novel postharvest technologies for stored-grain disinfestation and protection. An objective of this review is to indicate where new studies are required.

The widespread scientific activities on this subject resulted in the holding of several international conferences, such as the International Working Conferences on Stored-Product Protection held in Savannah, GA, in 1974 (Anonymous, 1975), in Ibadan, Nigeria, in 1978 (Anonymous, 1979), in Manhattan, KA, in 1983 (Anonymous, 1984), in Tel Aviv, Israel, in 1986 (Donahaye and Navarro, 1987), in Bordeaux, France, in 1990 (Fleurat-Lessard and Ducom, 1991), in Canberra, Australia, in 1994 (Highley et al., 1994), in Beijing, China, in 1998 (Zuxun et al., 1999), and in York, U.K., in 2002 (Credland et al., 2003). These meetings provided a platform for the useful exchange of information among the participating scientists and the reciprocal insemination of new ideas for further research.

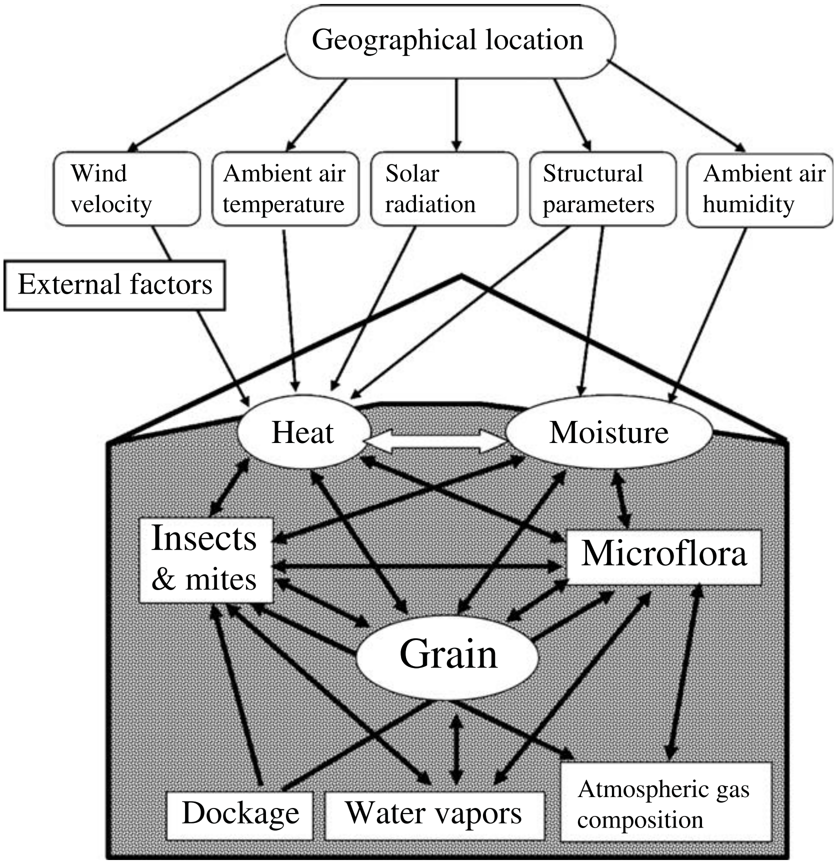

FIGURE 8.1 External factors and the interrelated grain bulk ecosystem components in unsealed bulks.

8.1.2 AN ECOSYSTEM APPROACH TO POSTHARVEST TECHNOLOGIES

It is useful to consider the storage ecosystem (Calderon, 1981; Sinha and Muir, 1973; Sinha, 1995) in order to understand the interaction between the many factors that influence the storage outcome (Figure 8.1). They are common to all stores whether they are high-tech silos or jute sacks for home-stored grain.

8.1.2.1 Components of the Ecosystem

The stored grain. This is the component of principal interest to us and the one we wish to protect from damage. Grain is a living organism, but because it is dormant its quality decreases extremely slowly.

The storage structure. The structure should protect the grain from external environmental factors such as rain and groundwater, minimize the influence of environmental temperature and humidity, and serve as a barrier to the ingress and contamination by insects, rodents, and birds.

Temperature. Ambient temperature is an abiotic factor that has little direct influence on grain condition, but greatly influences other biotic components (insects and microflora) and therefore indirectly affects conservation of grain quality.

Humidity. Ambient humidity is an abiotic factor of the air surrounding the grains. Within the confined storage space, the humidity of the intergranular air tends to reach equilibrium with the moisture of the grains. Its greatest influence is on molds, which develop at intergranular air humidities above 70%.

Atmospheric composition. The composition of the gases that constitute air is the third abiotic factor; it comprises about 50% of the volume of the storage structure and it fills the spaces between the grain kernels and the headspace above the grain.

Insects. About 250 species of beetles and moths infest stored grains. They are small enough to penetrate the interstices of the grain bulk, they have cosmopolitan distribution, and they have wide-ranging feeding habits. A small group of about 20 species are the major pests, and several of them attack crops in the field, thereby entering the ecosystem at the moment of loading the grain into storage (Navarro et al., 2001a).

Microorganisms. This biotic factor is composed of molds, yeasts, and bacteria. They are universally present on the grain, but are inactive when the equilibrium relative humidity (ERH) is below 65%.

When discussing microflora activity and preservation of grain quality, it is more meaningful to consider the moisture content of the intergranular environment or the equilibrium relative humidity corresponding to a particular grain moisture content. This is because various grain types may have different moisture contents at the same ERH (Figure 8.2). The microfloral activity and susceptibility of grain to deterioration is correlated to the ERH. An additional term frequently used in food microbiology is "water activity." Water activity (a_w) and ERH are numerically equivalent, but ERH is expressed as a percentage and a_w as a decimal of ERH, thus a_w. 0.8 = 80% ERH (Lacey et al., 1980).

Foreign matter (chaff, stalks, grain dust, sand, earth, stones**,** dockage, and so on). Its effects on the ecosystem are many: chaff and grain dust tend to absorb moisture more rapidly than grain and present a more suitable substrate for mold development than whole grains. Many insects that are unable to penetrate sound grain are able to develop well on this material. All small particles of material tend to block the interstitial air spaces.

8.1.2.2 Effects of Temperature

8.1.2.2.1 Effects of Temperature on Insects

Stored-product insects are mainly of tropical and subtropical origin and have spread to temperate areas via international trade. Because insects cannot control their body temperature, their rates of development and reproduction increase with rising temperature (up to a critical limit). Consequently most of them become inactive at low temperatures (10–15°C) and will die after prolonged periods at very low temperatures (0–5°C). Most species are unable to hibernate or enter an inactive phase, termed diapause, though some such as *Plodia interpunctella* and *Trogoderma granarium* can do so.

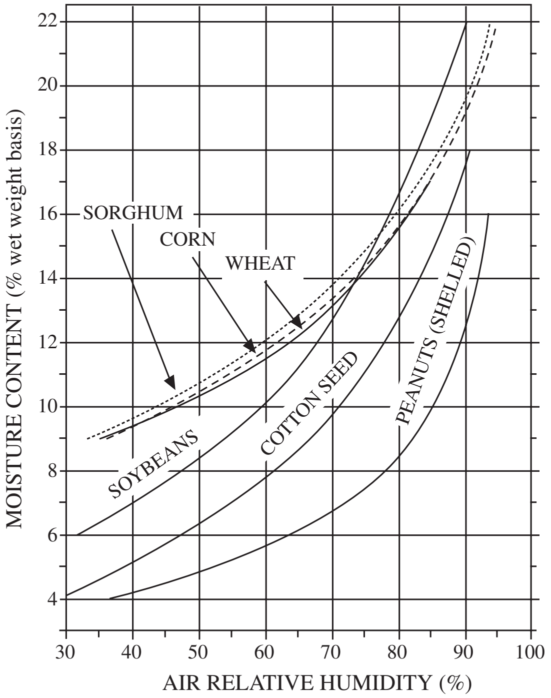

FIGURE 8.2 Moisture content/relative humidity curves of various commodities at 25ºC (absorption). References: Corn (Pixton and Warburton, 1971a); Cottonseed (Navarro and Paster, 1978); Peanuts (shelled) (Pixton and Warburton, 1971b); Sorghum (Ayerst, 1965); Soybeans (Larmour et al., 1944); Wheat (Coleman and Fellows, 1925).

For each insect species, a minimum and maximum temperature can be determined below or above which they are able to develop. These upper and lower limits are like "temperature windows"; the window for active growth is narrower than that for survival. Within the "temperature window" for survival, at certain low temperatures, oviposition and larval growth ceases, and at high temperatures egg sterility occurs and mortality increases. Conversely within the "temperature window" for growth, there is a temperature range at which oviposition and insect development are optimal. For example, survival of *Tribolium confusum* from egg to adult is highest between 25 and 27.5°C and decreases rapidly below and above this temperature (Howe, 1960). According to Fields (1992), mortality at low temperatures is a function of cooling rate, exposure time, temperature, and intrinsic growth rate. Insects become better acclimatized and survive low temperatures if grain cooling rates are slow.

Temperatures below 15°C generally arrest the development of pest species sufficiently to prevent damage, though not to cause mortality. For most stored-grain insects, sustained temperatures above 40°C and below 5°C are lethal (Table 8.1).

8.1.2.2.2 Effects of Temperature on Microflora

Although most of the microflora survive at low temperatures, they require fairly high temperatures for their development. According to temperature requirements,

TABLE 8.1
Response of Stored-Product Insects to Temperature*

Zone	Temperature (°C)	Effect
Lethal	50 to 60	Death in minutes
	45 to 50	Death in hours
Supraoptimal	35	Development stops
	33 to 35	Development slows
Optimal	25 to 33	Maximum rate of development
Suboptimal	13 to 25	Development slows
	13 to 20	Development stops
	5 to 13	Death in weeks to months (unacclimated)
Lethal, movement stops	0 to 5	Death in weeks (unacclimated)
	–10 to 0	Death in days to weeks (unacclimated)
	–25 to –15	Death in minutes to hours, insects freeze

* Species, stage of development, and moisture content of food will influence the response to temperature.

Source: Compiled and revised from Fields, 1992.

the storage microflora may be separated into three groups as in the following (Jobber and Jamieson 1970):

1. *Psychrophilic* These are the cold-resistant species that can survive and develop at a lower range of temperatures than other groups of storage microflora. They include *Aspergillus glaucus* (min. –8°C), *Penicillium digitatum* (min. –3°C), and *P. rugulosum* (min. 0°C).
2. *Mesophilic:* This group includes the major species of storage molds such as *Aspergillus flavus* (min. 6–8°C, optimum 36–38°C, max. 44–46°C); *Aspergillus niger* (min. 6–8°C, optimum 35–37°C, max. 46–48°C).
3. *Thermophilic:* These are fungi, bacteria, and *Actinomycetes* that can develop and survive at fairly high temperatures. Species in this group include *Aspergillus fumigatus* (which can survive at 57–58°C and is commonly found in grain undergoing "spontaneous heating"); *Penicillium duponti* (which can develop at a maximum of 60°C); and *Bacillus calfactor* (found in, and apparently responsible for, spontaneous heating of hay, up to 70°C).

Lowering the temperature of grain will not eliminate the microfloral population, since many species can survive and even develop at subzero temperatures. However, it does suppress most microfloral growth, since most of the fungi are mesophilic species.

8.1.2.3 Effects of Moisture and Relative Humidity

8.1.2.3.1 Effects of Moisture and Relative Humidity on Insects

Insect pests depend on their food supply to obtain the moisture they require for their life processes. Up to a certain point, the higher the moisture of the grain, the higher the rate of increase of insect pests. Above the "critical moisture content" where molds are able to develop, there is a negative effect on the quality of the food supply that in turn affects insect development. Moisture requirements differ with different species of insects.

Rice weevils (*Sitophilus oryzae*) are unable to breed in grain with moisture contents below 9%, and adults soon die in dry grain. However, at high temperatures their ability to survive and reproduce is greater. *R. dominica* can breed in wheat at 8% moisture content at 35°C. *T. granarium* is capable of utilizing metabolic water and can survive on grain at 1% moisture content. *Tribolium* spp. can survive on bran and wheat flour at low moisture contents.

8.1.2.3.2 Effects of Humidity on Microflora

Microorganisms are unable to multiply when the ERH is below 65%, although it is generally accepted that to protect stored grain from mold the maximum ERH should be 70%. Favorable conditions occur when the moisture content of the grain or the relative humidity of the intergranular atmosphere rises above a certain threshold. This threshold is generally considered to be around 75% RH (termed the critical relative humidity) or the corresponding equilibrium moisture content of the grain (e.g., for wheat it is about 14%; Figure 8.2), often termed its critical moisture content. Beyond this threshold, microflora become activated and start to grow, accompanied by active respiration (liberation of metabolic heat and water). At humidity or moisture conditions above this level, deterioration increases at an exponential rate.

The availability of water in the food medium is a vital factor determining both the types of bacteria or fungi capable of growth, and the rate at which they can grow. It is usually measured in term of water activity and is a function of the moisture content of the food.

Bacteria grow best at water activities near to unity and will not grow at a water activity less than about 0.95. Yeasts occupy an intermediate range, and they will grow at a water activity as low as 0.85. Fungi are more resistant to the effect of dry conditions; although the vast majority are inhibited by a water activity lower than 0.70, a very few species will show some growth at a water activity as low as 0.65 (Lacey et al. 1980) (Table 8.2).

TABLE 8.2
Limiting Water Activity (a_w) for Mold Growth*

Temperature (°C)	–5	0	5	10	20	27.5	30	35	40	45
Experimental Data (a_w)	0.953	0.910	0.882	0.782	0.698	0.673	0.678	0.703	0.765	0.828

* At a_w levels below the limiting experimental values, molds do not grow, or grow very slowly. Above the limiting values, mold growth is possible (compiled from Lacey et al., 1980).

8.1.2.4 Effects of Atmospheric Gas Composition on Insects and Microflora

8.1.2.4.1 Effects on Insects

Storage insects are aerobic organisms requiring oxygen for their survival. Therefore, they respond to altered atmospheric gas compositions containing “low O_2” or “high CO_2” concentrations. Low O_2 atmospheres typically contain less than 1% O_2, with the balance being N_2 and very low concentrations of the other atmospheric gases, namely CO_2 and the inert atmospheric gases. They function largely by their anoxic effect. Conversely, to have an insecticidal toxic effect, a “high CO_2” atmosphere must contain a substantial proportion of CO_2, often more than 60%. Insect response depends on the species, developmental stage, and age. It also depends on the physical conditions in the environment, mainly temperature, humidity, and the partial pressure, as well as exposure time and the type of atmospheric composition used as treatment.

Nitrogen causes a progressive hypoxia or anoxia when used alone at a high purity level. Generally the lower the oxygen level, the higher the mortality. For effective control, the O_2 level should be < 3% and preferably < 1% if a rapid kill is required (Navarro, 1978; Banks and Annis, 1990; Fleurat Lessard, 1990). This effect was shown to be reversed for adult rice weevils, *Sitophilus oryzae,* which below 1% oxygen in nitrogen showed tolerance, increasing the lethal exposure time, apparently due to the closure of weevils their spiracles to prevent desiccation (Navarro et al., 1985). In particular, *S. oryzae* adults are killed more quickly (within 24 h) at 1.0% O_2 rather than at 0.1 or 2% O_2 under the same conditions (Figure 8.3).

8.1.2.4.2 Effects on Microflora

Most of the organisms composing the grain microflora are aerobic. These include some fungi responsible for development of mycotoxins. Since they are unable to develop in the absence of oxygen, the principle of hermetic storage is in theory very applicable for preventing fungal development.

If the storage bin or container has a very high level of hermetic seal, respiration of fungi on the grain will consume the oxygen, replacing it with carbon dioxide until virtually no oxygen remains, at which time the fungi cease to develop. However, this level of hermetic seal is difficult to achieve, particularly in very large storage structures**,** where the seal must be complete.

The use of hermetic storage to control microflora is most applicable for intermediate-moisture-content grain because the mesophytic fungi are all aerobic. However, at higher moisture contents, the hydrophytic bacteria and actinomycetes can develop anaerobically to produce fermented, sour grain. This is not suitable for grain destined for human consumption, but is applicable for high-moisture grain destined for animal feed and in well-sealed silos designed for storage of silage.

8.2 PHYSICALLY BASED TECHNOLOGIES FOR MANIPULATING THE STORAGE ECOSYSTEM

Physical control techniques were the main methods for grain protection before the extensive use of synthetic pesticides, and even today pest control in many systems

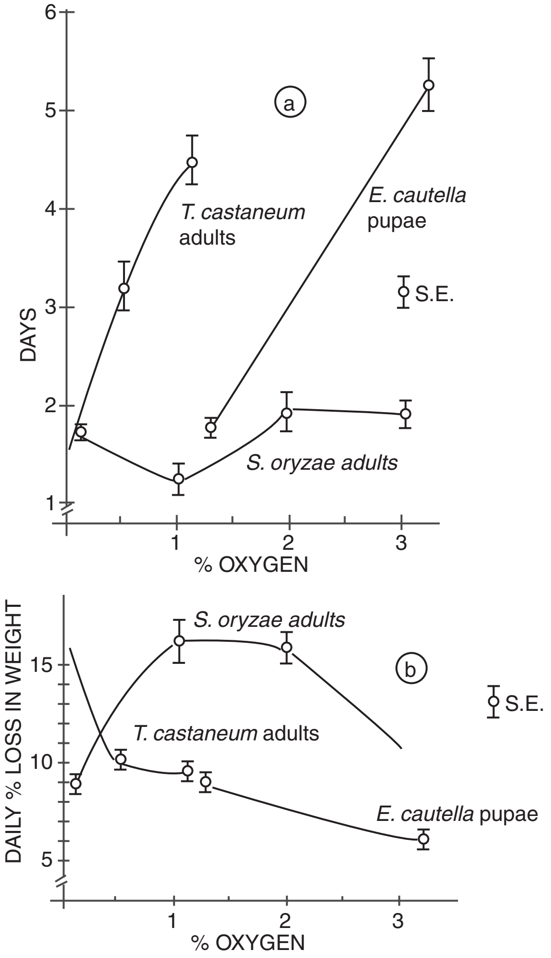

FIGURE 8.3 The relationship between oxygen concentration and the time required for LT_{95} (a) and the effect on daily percent loss in weight (b) of three stored-product insects at 54% RH and 26°C. (Navarro, 1978. With permission.)

of traditional and subsistence-level grain storage is based largely on physical control techniques (Banks and Fields, 1995). Among the techniques to be reevaluated have been sun drying (Murdock and Shade, 1991), pit storage (Hyde et al., 1973; Levinson and Levinson, 1989), admixture of ground rock and ash (Ebeling, 1971), and winnowing and sieving (Banks, 1987). All these categories of physical control techniques have been a process of rediscovery and adaptation, rather than development of new processes.

The application of these alternative control methods has involved modification of the control concept, and modification of the systems of commodity handling and storage to suit the modern large bulks of grain storage with high rates of handling, and possibly an increased tolerance to low levels of insect infestations. Unlike chemical pesticides, where high levels of mortality (over 99.9%) and rapid action (a few days or less) are expected, physical control methods tend to be slower with a compromise towards lower levels of insect kill.

There have been several general reviews of physical control of stored-grain pests, more recent ones being those by Banks and Fields (1995) and Subramanyam and Hagstrum (2000). Most of these reports have considered the effects of particular methods, while a very few attempted to study the effectiveness of integrated methods such as heat and inert dusts (Fields et al., 1997). The combined effects of various methods are nevertheless an important aspect of the study of physical control of pests.

Many of these methods provide no post-treatment protection of the disinfested product against reinvasion. Therefore, adaptation by the grain industry of physical methods will require a much higher level of understanding and management than chemical control methods.

8.2.1 MANIPULATION OF TEMPERATURE

8.2.1.1 Low Temperatures

8.2.1.1.1 Preservation of Stored Grain by Aeration

An acceptable practice to reduce the commodity temperature is to use mechanical aeration by means of fans. It can be easily applied to stored grain or granular commodities. Aeration may be defined as "the forced movement of ambient air of suitable quality or of suitably conditioned air through a grain bulk for improvement of grain storability" (Calderon, 1972). Aeration is also called "active," "mechanical," "low volume," or "forced" ventilation, since fan power is used to deliver the air.

Aeration should be distinguished from "passive" or "natural" ventilation, which takes place in grain bins with an open manhole, or in granaries with open doors or windows, and is due to natural or convective air currents. Passive aeration takes place also in corn cribs, used traditionally in tropical and subtropical climates. Wind forces ambient air to flow through corn (maize) cribs, causing slow drying of damp unshelled corn and other grains.

Aeration is a widely used method for the preservation of stored grain. It is used to modify the grain bulk microclimate and to render it unfavorable for the development of damaging organisms in the grain, and at the same time create favorable conditions for the sustained preservation of grain quality. Within the concept of the storage ecosystem, the role of aeration is to modify one or more of the abiotic factors (temperature, humidity, atmospheric composition) and thereby to "condition" the stored grain to improve existing conditions in the grain bulk by moving air of suitable quality through the grain mass.

Forced aeration is an effectively applied method in commercial-scale bulk storage of grain and takes advantage of two important physical properties of the grain bulk:

1. Porosity of the grain bulk: For most cereal grain, the intergranular void volume is 35–55% of the grain bulk volume. The porous nature of bulk grain permits forced air to pass through and come into contact with almost all grain kernels in the bulk.

2. Thermal insulation property of the grain bulk: Due to low thermal conductivity, the grain mass is self-insulating. This enables maintenance of a “modified microclimate” long after the grain bulk has been aerated.

Although the role of temperature has long been recognized, manipulation of this regulation by aeration techniques was first brought into focus in the early 1950s. Since then several authors have reported their findings on aeration carried out in temperate climates. The knowledge accumulated over the last four decades has formed the basis for the present-day aeration technology recently reviewed by Navarro and Noyes (2002). At present, forced aeration of grain is one of the most effective nonchemical methods in use for the control of stored grain conditions, biological activity, and grain quality losses.

8.2.1.1.2 Preservation by Chilling of Grain by Refrigerated Air

Aeration using ambient air may not be sufficient to control fungi on moist grain, protect grain against mites and insects, control self-heating of grain, or preserve the germination capacity and quality of stored grain in warm climates, or when warm grain is stored immediately after harvest. In answer to these situations, refrigerated-air units for chilling grain have been developed for commodities that can justify the added expense of refrigerated aeration cooling. In this type of aeration process, ambient air is conditioned by passing it through the evaporator coil and a secondary reheat coil of the refrigeration unit, and then blowing the chilled air into the grain bulk via the existing aeration system (Figure 8.4). Passage through the secondary reheating coil is designed to adjust the air relative humidity to 60–75% to match the target moisture content of the dry grain. The amount of reheating and the final air temperature are adjustable by the operator to achieve the desired aeration conditions.

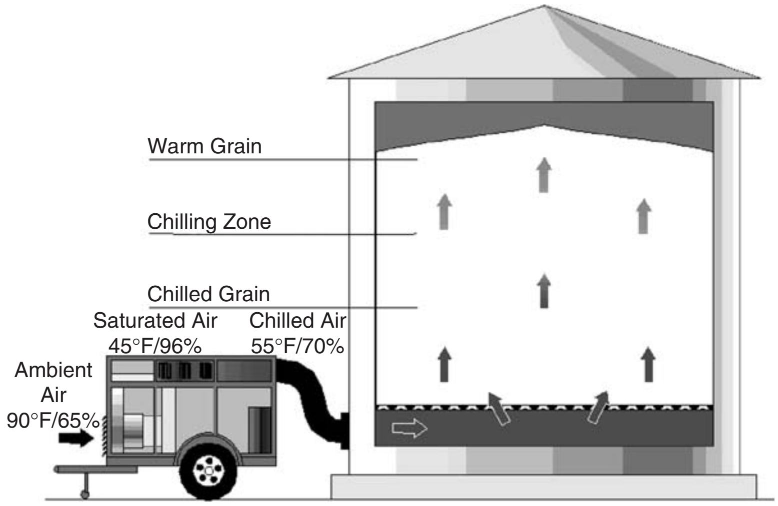

FIGURE 8.4 Schematic presentation of the grain-chilling process.

Refrigerated aeration has been used for cooling dry grain in subtropical climates when ambient temperatures are too high for successful insect control by aeration with untreated air (Hunter and Taylor, 1980; Navarro et al., 1973). Refrigeration involves considerable investment, but together with the dehumidified air method, it could provide answers to the practicability of aeration for safe commercial storage in tropical climates.

In many grain-growing areas of the world the moisture content of grain at harvest is too high for safe storage. This damp grain is readily attacked by molds unless it is protected in some way. The most widely used method of preventing mold growth is to dry the grain to a safe level. Burrell (1982) argued that there is a balance between "safe moisture content" and "safe temperature": The lower the temperature of bulk grain, the damper it can be safely stored. This leads to the conclusion that drying need not be so stringently applied since the power required to evaporate moisture from a bulk of grain is far greater than that required to cool the same bulk.

For example, the energy required to evaporate 6 percentage points of moisture from a grain mass is at least six times greater than that required to cool the same bulk from 25°C to 5°C by using refrigerated air. Therefore, chilled storage may have an economic advantage over drying. This advantage is even retained when storing excessively damp grain, which requires frequent rechilling, including the high capital investment costs for equipment.

In the major study *Enhancing the Quality of U.S. Grain for International Trade* (U.S. Congress, 1989), the maintenance of low temperature and moisture levels in bulk-stored grain was identified as the primary way to preserve grain quality and prevent damage from molds and insects. Grain chilling is a technology that can be successfully applied under many climatic conditions to preserve grain quality during storage when commodity value and profit margins are sufficient. It permits the short- to long-term storage of grain independent of the ambient conditions. Grain chilling has been applied commercially in over 50 countries during the past 40 years but has only recently gained recognition in the United States (Maier, 1994).

It is estimated that over 80 million tons of grain are cooled annually worldwide with grain-chilling systems. Grain chilling is accepted as a grain conditioning technology in much of western Europe; currently most new units appear to be marketed in Southeast Asia. In the 1960s grain chillers were primarily used as a means of preserving high-moisture (moist, damp) grain. Later, grain chilling was applied to improving storability of sensitive commodities subject to development of heat foci (hot spots), i.e., for soybeans and maize, and preserving the quality of high-value dry grain, seeds, and edible beans, primarily against mites and insects (Navarro and Noyes, 2002).

8.2.1.2 High Temperatures

The lethal effect of temperatures from 42°C to 50°C has been subject for a study by Gonen (1977a, 1977b) and Menon and Subramanyam (2000). There is significant survival (< 95% mortality) of several species when exposed for some hours at this range of temperatures. Fields (1992) has listed the results of studies on the susceptibility of stored product pests to temperatures greater than 50°C. The information suggests that exposure of 2 h at 50°C should eliminate all pests, but studies on heat-tolerant species and stages (e.g., *R. dominica* pupae) are lacking (Banks and Fields, 1995). To control the most heat-tolerant common pest, *R. dominica*, Evans (1987) concluded that a grain temperature of 65°C must be attained briefly. Such temperatures can damage the baking quality of wheat, the malting quality of barley, and the germination of most seeds. Thus the temperature of the grain must be carefully measured and controlled. Effects of high temperatures have been concentrated on obtaining rapid disinfestation without damage to the treated grain (Banks and Fields, 1995).

8.2.1.2.1 Heat Sterilization in Flour Mills

The heat sterilization technique in flour mills and food processing facilities uses high target temperatures ranging from 54°C to 60°C to kill stored-product insects by inducing dehydration or protein coagulation or enzyme destruction. The length of time required to destroy stored-product insects varies from a few hours within a piece of machinery to up to 24 hours for a large facility. The key to successfully eradicating the insects is in achieving the target temperatures for a long enough period of time to reach lethal temperatures in areas such as machinery interiors, voids, dust collectors, and piping where stored-product insects may be found (Heaps, 1988).

8.2.1.2.2 High-Frequency Dielectric and Microwave Heating

Studies with a variety of means of heating grain — by infrared, high-frequency (dielectric), and microwave heating — all appear to achieve the same lethal effect on insects. Insect tissue has a higher moisture content than the dry stored commodities and therefore it absorbs more energy than the commodity itself. Thus insects are heated selectively and more rapidly than grain with microwaves (Nelson, 1986). Bedi and Singh (1992) claim some difference in mortality when using microwave frequencies of 12, 15, and 18 GHz. This aspect of using radio frequencies or microwaves will be further elaborated in Section 8.2.5.1.

8.2.1.2.3 Fluidized Bed for Heating Grain

Effects of high temperatures were studied on obtaining rapid disinfestation without damage to the treated grain. Comparisons of the heat susceptibility of stored-product pests at temperatures above 50°C are confounded by the difficulties in accurate measurement of the temperature to which the target insect was actually exposed and the lack of a system that allows different temperature-exposure time combinations to be evaluated (Fields, 1992).

For the application of heat disinfestation in modern commodity storage systems, several approaches have been adopted. However, the target commodity-temperature to achieve disinfestation appears to be similar for all these approaches. Among them fluidized-bed heating is the only heat disinfestation process developed to the full-scale prototype stage for treatment of over 150 tonne/hour of grain (Banks and Fields, 1995). Fluid-bed heating involves passing hot air through a shallow layer of grain under controlled velocity conditions to create a fluidized state in which the grains are temporarily suspended in the hot air current. The other approaches for heat disinfestation have only been demonstrated successfully at the laboratory or pilot plant stage of development (Sutherland et al., 1986).

The fluidized-bed heating and other hot air systems have the advantage that they can easily be adapted for cooling the treated grain after exposure. Cooling is necessary, as holding grain for more than brief periods at temperatures that control insects (over 60°C) affects the qualities of grain, such as germination and baking quality.

Heat disinfestation is both capital and energy intensive. Running costs for fluidized-bed heat disinfestation were calculated to be similar to the cost of using chemical protectants (organophosphorous contact pesticides) under Australian conditions without including the cost of equipment (Sutherland et al., 1986).

The quality of treated material can be diminished if temperatures are too high or if durations are too long (Fleurat-Lessard, 1985; Evans, 1987; More et al., 1992). When any heat disinfestation procedure is examined, the effects on end use quality must also be tested. In general, the conditions needed to control insects do not affect quality, but the margin of safety before damage occurs is narrow. Therefore, close control of the heating process and subsequent cooling is essential.

8.2.1.2.4 Disinfestation of Dry Fruits

Lindgren and Vincent (1953) showed in the laboratory that exposure to 49°C for 4 to 20 min killed 90% of adult nitidulids, although this figure was influenced by RH. Al-Azawi et al. (1984) showed that under laboratory conditions, adults of the dried fruit beetle, *Carpophilus hemipterus,* were tolerant to heat with exposures of from 25 to 60 min at 50°C being required to achieve complete mortality. For complete mortality of all stages of *Cadra cautella* on stored dates, exposure to 60°C for 33 min was required (Al-Azawi et al., 1983).

In the drying process of dried fruits and nuts, temperatures are kept usually moderate (35 to 55°C) to avoid commodity damage. Temperatures used for drying Madjoul dates in Israel should be kept within the range of 45 to 55°C to avoid the blistering effect that separates the skin from the pulp of the fruit. However, studies that consider not only control but also emigration of nitidulid beetles from dates using heat during the drying process were lacking in the literature until now. Emigration that causes the insects to abandon the fruit is perhaps more important than killing them, since it actually disinfests the fruit, thereby improving its quality. With this approach in mind it was considered possible that heat treatment may be effective in producing emigration and control of nitidulid beetles of dates. Recently, the effectiveness of heat in causing emigration and mortality of *Carpophilus* spp. larvae from dates was compared (Navarro et al., 2003a, 2004). It was shown in the laboratory that the average disinfestation value obtained was greatest at exposure to 50°C (92.3%) and this differed highly significantly from disinfestations levels at 40°C and 55°C (Navarro et al., 2004). Previous data that reported disinfestation levels obtainable by using methyl bromide indicated that the highest disinfestation did not exceeded 90% (Donahaye et al., 1991b, 1992). In their recent study Navarro et al. (2004) showed that the highest mortality values reaching 100% were obtained at 50°C and 55°C.

In field trials, Navarro et al. (2004) demonstrated the feasibility of applying heat for the disinfestation of dates using a date-drying facility. The target temperature of 50°C could be achieved within 1 h after the introduction of the dates into the drier. An additional two hours were necessary to achieve emigration and mortality of the insects. The bioassay of infested dates resulted in total emigration and mortality of larvae. These aspects of the heat treatment are currently under investigation.

The heat treatment is intended to replace the conventional fumigation with methyl bromide, within the framework of studies to find MB alternatives. Since dates are first disinfested using methyl bromide and then dried when necessary, it is expected that this treatment will be most suitable for dates that are subject to drying before storage. As for dates that are already at their moisture content suitable for storage (such as the Deglet-Nur variety), exposure to heat will last no more than 2 h after the dates reach the target temperature. Preliminary experiments have shown that at a short exposure of 2 h, an insignificant moisture reduction of dates is incurred (Navarro et al. 2004).

8.2.2 MODIFIED ATMOSPHERES

8.2.2.1 Definitions and Uses of MA

The objective of modified atmosphere (MA) treatments is to attain a composition of atmospheric gases rich in CO_2 and low in O_2, or a combination of these two gases at normal or altered atmospheric pressure within the treatment enclosure, for the exposure time necessary to control the storage pests and preserve the quality of the commodity. Terms that define the same method of treatment for the control of storage insect pests or for the preservation of food include CA, sealed storage, or atmospheres used at high or low pressures. Therefore, an attempt is made here to propose definitions that will add clarity to the available storage insect control methods whether at normal atmospheric pressure or under altered atmospheric pressure.

Modified atmosphere is proposed to serve as the general term, including all cases in which the composition of atmospheric gases or their partial pressures in the treatment enclosure have been modified to create in it conditions favorable for the control of storage insects and preserve the quality of the commodity. In an MA treatment, the atmospheric composition within the treated enclosure may change during the treatment period. This term will comprise all the following designations.

8.2.2.1.1 MAs under Normal Atmospheric Pressure

Controlled atmosphere (CA) is a modified gas composition, usually produced artificially, and maintained unchanged by additionally generating the desired gases (CO_2 or N_2) or by further purging the storage with these gases, supplied from pressurized cylinders or otherwise (Figure 8.5). This supplementary introduction of gases is carried out when their concentration in the sealed container falls to below the desired level. The CA method is intended to rectify changes caused by possible small leakages of gases (that cause the increase of O_2 or decrease of CO_2 content in the enclosure), which are almost impossible to avoid. Thus, the term CA, although commonly employed as the one describing the entire subject, has actually its own limited and specific meaning.

Hermetic storage is a type of MA that can be applied for the protection of grain; it is also called “sealed storage,” “airtight storage,” or “sacrificial sealed storage.” This method takes advantage of sufficiently sealed structures that enable insects and other aerobic organisms in the commodity or the commodity itself to generate the

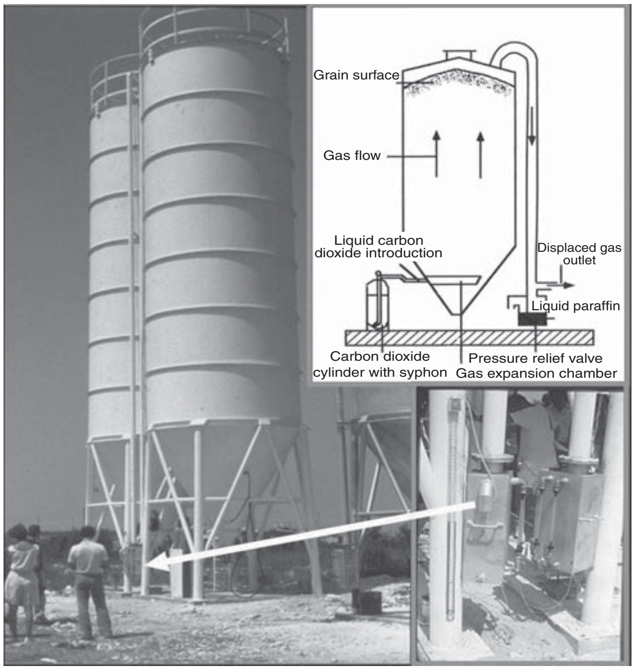

FIGURE 8.5 Application of carbon dioxide-based MA on a silo bin and the schematic presentation of the application process.

MA by reducing the O_2 and increasing the CO_2 concentrations through respiratory metabolism.

Assisted hermetic storage is another type of hermetic storage that uses exothermic gas generators, catalytic oxygen converters, or respiration gases of plant material. In this type of hermetic storage, the atmosphere has been modified by the supply of an atmosphere generated externally from the storage container, so that a gas composition of low-oxygen (< 1%) and high-carbon dioxide atmosphere can be achieved artificially, by using exothermic or catalytic gas generators. The exothermic gas generators burn fossil fuels to generate the low-O_2 atmosphere. The catalytic oxygen converters burn propane or butane by catalytic conversion processes without flame. Oxygen can also be removed from the air by respiration using various plant materials or wastes placed in a generator externally.

8.2.2.1.2 MAs under Altered Atmospheric Pressure

Vacuum treatment. In a low-pressure environment there is a close correlation between the partial pressure of the remaining O_2 and the rate of kill. Until recently this treatment could only be carried out in specially constructed rigid and expensive vacuum chambers. A practical solution has been proposed named vacuum hermetic fumigation (V-HF) process that uses flexible liners. To achieve the low pressures in the flexible liners, sufficiently low pressures (25–50 mmHg absolute pressure) can be obtained (using a commercial vacuum pump) and maintained for indefinite periods of time.

High-pressure carbon dioxide treatments can be significantly shortened to exposure times that may be measured in hours using increased pressure (10–37 bar) applied in specially designed metal chambers that withstand the high pressures. Because of the high initial capital investment, these high-pressure chamber treatments may be practical only for high-value products such as spices, nuts, medicinal herbs, and other special commodities.

8.2.2.2 Effects of MA on Stored-product Insects and Mites

8.2.2.2.1 Low Oxygen and Anoxia

Nitrogen is commonly used to produce a low-oxygen atmosphere. For effective control, the O_2 level should be $< 3\%$ and preferably $< 1\%$ if a rapid kill is required (Banks and Annis, 1990; Fleurat Lessard, 1990; Navarro, 1978; Adler et al., 2000).

8.2.2.2.2 High Carbon Dioxide and Hypercarbia

Atmospheres containing about 60% carbon dioxide rapidly kill stored-product insects. At 26°C, about 4 days of exposure would be sufficient to kill all stages (including eggs) of most stored-product insects. When the concentration level in CO_2 is reduced to about 35%, after 10 days of exposure, less than 1% of *T. confusum* larvae survived the treatment (Ronai and Jay, 1982). This concentration seems to be the target level above which carbon dioxide poisoning occurs (Jay and Pearman, 1973). Laboratory tests on the major stored-product insects have shown that adults can be killed with pure CO_2 within 10 to 48 h, whereas exposure times of more than 14 days are required to kill them when the atmosphere contains less than 40% CO_2, even at temperature levels above 20°C (Kashi, 1981). The symptoms of carbon dioxide poisoning in insects initially include a narcotic effect leading to a knockdown, i.e., immobilization of the insects under carbon dioxide-enriched atmospheres (Edwards and Batten, 1973).

There are more laboratory data for *S. oryzae* than any other stored-product pest and, excluding *Trogoderma* spp., it appears to be the most tolerant of high-CO_2 atmospheres. The minimum concentration required to control all developmental stages of *S. oryzae* is slightly less than 40% (Table 8.3). Eggs are significantly affected by 20% CO_2, while at $> 20\%$, adult insects are the most susceptible stage (Banks and Annis, 1990; Navarro and Jay, 1987).

Diapausing *Trogoderma granarium* larvae are the most tolerant to high-CO_2 atmospheres of any species and stage so far reported (Annis, 1987). They are tolerant of CO_2 concentrations of 60% or less in air at 25°C, and less than 95% mortality has been obtained after 25 days, the longest exposure so far tested. It appears that diapausing *T. variabile* larvae may have a similar response (Banks and Annis, 1990). Other *Trogoderma* species are also very tolerant (Jay, 1984b).

8.2.2.2.3 Combinations of Low Oxygen and High Carbon Dioxide

Researchers have been interested in increasing the efficacy of MA on insects by attempting to combine very low oxygen in combination with very high carbon dioxide concentrations. However, increasing the carbon dioxide concentration in

TABLE 8.3
Suggested Provisional Dosage Regimes for Control of All Stages of the 12 Most Common Insect Species of Stored Grain, Using Modified Atmospheres at Temperatures between 20 and 29°C

Atmospheric Gas Concentration Constant % CO_2 in air	Controls Most Common Grain Insects Including *Trogoderma granarium* (Yes/No)	Exposure Period (Days)
40	No	17
60	No	11
80	No	8.5
80	Yes	16
CO_2 decline in air from > 70 to 35%	No	15

Source: Compiled from Annis, 1987.

the normal atmosphere reduces proportionally the partial pressure of the oxygen available to insects. Gas burners or fossil fuel burners also have the capability to generate a combination low in oxygen and high in carbon dioxide. For example, a typical propane burner would produce an atmosphere of 0.5% oxygen, 13.5% carbon dioxide, 1% nitrogen, and 1% argon. Therefore, unless a mixture of nitrogen and carbon dioxide or a gas burner atmosphere is used, the simplest way to achieve a low-oxygen and high-carbon dioxide atmosphere is by using carbon dioxide in air (Storey, 1975).

In the case of hypoxia (2 to 5% O_2), when a small proportion of CO_2 (5 to 40% CO_2) is added to the initial mixture of N_2/O_2, the mortality rate increases considerably (Calderon and Navarro, 1979). When CO_2 is added to low-O_2 atmospheres, there is a synergistic effect, which is obvious from the significant interaction between the concentrations of these two gases (Calderon and Navarro, 1980).

8.2.2.2.4 Effects of Low Pressures

It has been shown that mortality of insects under low pressures is caused mainly by the low partial pressure of oxygen, resulting in hypoxia (Navarro and Calderon, 1979). The partial pressure of oxygen has a decisive effect on insect mortality, while no significant function could be attributed to the low pressure itself. At 50 mm Hg the partial pressure of oxygen is equivalent to 1.4% O_2, this being similar to the target oxygen concentration under a modified atmosphere obtained by nitrogen flushing. Finkelman et al. (2003b) conducted experiments in a calculated atmospheric partial pressure equivalent to an oxygen concentration of 1.3–1.8%. This oxygen level is close to critical levels needed for insect disinfestations using low oxygen levels achieved by displacement with nitrogen (Donahaye, 1992). Finkelman et al. (2004a) showed that less than 3 days under 50 mm Hg at 30ºC would control all stages of *Ephestia cautella*, *Plodia interpunctella,* and *Tribolium castaneum*, the times needed to obtain 99% mortality being 45 h, 49 h, and 22 h, respectively. The eggs of all three species were the most tolerant to low pressure.

Additionally, according to Finkelman et al. (2004b) when *Trogoderma granarium*, *Lasioderma serricorne,* and *Oryzaephilus surinamensis* were subjected to 50 mm Hg at 30°C, the egg was again the most tolerant stage in all three species, the times needed to obtain 99% mortality being 46 h, 91 h, and 32 h, respectively. Adults of *T. granarium* and *L. serricorne* and pupae of *O. surinamensis* were the most susceptible.

8.2.2.2.5 Effects of High Pressure

Extremely short exposure times of a few hours are needed to control all stages of storage insects with carbon dioxide at pressures between 10 and 37 bar. Generally, increasing the pressure reduces the lethal exposure time.

Exposure of *L. serricorne*, *O. surinamensis*, *T. castaneum*, *T. confusum*, *T. granarium*, *Corcyra cephalonica*, *Ephestia elutella*, *E. cautella*, *P. interpunctella*, and *S. cerealella* to carbon dioxide at 37 bar for 20 min, 30 bar for 1 h, and 20 bar for 3 h at 20°C resulted in 100% mortality of all insects. However, survivors of *T. confusum* were found after treatment with 10 bars for 20 h. Only *Cryptolestes turcicus* survived all tested pressures and exposure times. Consequently, Adler et al. (2000) concluded that extrapolation of laboratory results with carbon dioxide and high pressures to field situations are risky. The rate of decompression of pressurized storages may also have an impact on insect mortality (Ulrichs, 1994; Ulrichs et al., 1997a, 1997b).

8.2.2.3 The Effect of MA on Preventing Mold Growth and Mycotoxin Formation

In recent years, the use of modified atmospheres has been considered as a potential means to replace chemical control. Working with fungi isolated from moldy flue-cured tobacco, Yang and Lucas (1970) noted that a level of 0.5% O_2 totally inhibited the growth of some of the fungi, including *A. amstelodami, A. repens, A. ruber,* and *Cladosporum herbarum,* but not of *A. flavus, A. niger,* and *A. ochraceus*. Additionally, Wilson and Jay (1975) reported that the growth of *A. flavus* and *F. moniliforme* on corn grains was not arrested in atmospheres containing 0.5% O_2, although deterioration of the grain was delayed. The ability of some mold species to survive under low O_2 or high CO_2 concentrations was demonstrated over a large range of conditions.

Wells and Payne (1980) reported that the number of fungal colonies isolated from pecan kernels held in 21% O_2 + 3% CO_2 (at 21°C) was significantly lower than in air. Increasing the CO_2 levels from 3 to 30% (21% O_2) was concomitant with a further decrease in colony counts from the kernels. Although 1% O_2 in nitrogen had no effect on survival of mycoflora, when 1% O_2 was combined with 30% CO_2, the level of the fungal counts was significantly lower compared with those recorded from the 1% O_2 or the 21% O_2 + 30% CO_2 treatments.

The effect of gas combinations on developmental stages other than mycelial growth, such as lag phase, sporulation, and germination, was also studied. The duration of the lag phase of some *Aspergillus* and *Penicillium* spp. was negatively correlated with a_w and O_2 concentrations and was positively correlated with CO_2 concentrations (Magan and Lacey, 1984). The latent periods for growth of storage fungi in O_2 concentrations lower than 1% (close to the growth limits) were longer than of the field fungi grown under threshold O_2 concentrations. The storage fungi were much more tolerant of low a_w than were the field fungi. Increasing CO_2 to 15% resulted in an increase in the lag phase at all a_w levels tested without marked differences between the field and the storage fungi. The extension of the latent period until mold appearance on corn stored under MA was reported by Wilson and Jay (1975). When they stored corn in an atmosphere of 61.7% CO_2 + 8.7% O_2 + 29.6% N_2, visible mold appeared 3 weeks later than the appearance of visible mold in the control. When spores of *P. patulum* were exposed to CO_2 levels ranging from 10 to 60% in 20% O_2, the colonies appeared 2 to 4 days later than in the control (Paster et al., 1986).

Aerobic fungi are predominant in bulk grain and they can proliferate and multiply extensively in air of normal composition. If the amount of O_2 is reduced and CO_2 accumulates, the viability of the fungi expressed as rate of growth, degree of sporulation, or respiratory rate, as well as their ability to attack the grain tissues, is suppressed. However, a distinction must be made between different species on the basis of their tolerance to low O_2 or high CO_2 concentrations. In many studies in which the O_2 requirements of fungi as well as the effect of anaerobiosis on their growth were determined, N_2 was used to modify the CO_2/O_2 ratios. Storing grains in a N_2 atmosphere was found to be effective in preventing mold growth (Shejbal, 1980). Richard-Molard et al. (1980) reported that under pure N_2, the initial microflora decreased quicker at 23% moisture content than at 17% moisture content.

Serafini et al. (1980) compared the sensitivity of *A. flavus, A. chevalieri,* and *P. cyclopium* exposed to N_2 (with 0.01% O_2) using wheat grains. All the tested strains showed a considerable decrease in their rate of growth under the conditions of complete anoxia, with *P. cyclopium* and *A. chevalieri* being the most sensitive (total inhibition after 21 days).

The effect of various combinations of atmospheric gases on the production of mycotoxin was investigated, particularly with regard to aflatoxins. Epstein et al. (1970) studied the production of aflatoxins B1 and G1 by *A. flavus* grown on a liquid medium and found that at any given temperature, less aflatoxin was produced under the MA compared with the control (ambient air). Landers et al. (1986) found that aflatoxin production in groundnuts decreased as CO_2 concentrations rose from 0.03 to 100% or O_2 concentrations decreased from 21 to 1%. The authors concluded that high concentrations of CO_2, rather than low concentrations of O_2, were the primary cause of inhibition of aflatoxin production under optimal temperature and moisture conditions for mold growth. It seems likely that mycotoxinin formation could be controlled by enriching the atmosphere with CO_2 or by reducing the O_2 concentration. The inhibitory concentrations are not lethal for the mycotoxigenic fungi, and after the colonies are returned to normal atmosphere, mycotoxins can be produced.

8.2.2.4 Effects of MA on Product Quality

8.2.2.4.1 Germination of Seeds

Seeds below their critical moisture content are not significantly affected at high-CO_2 or low-O_2 atmospheres (Banks, 1981). However, with increasing grain moisture contents, CO_2-rich atmospheres could reduce the physiological quality of grain by interfering with the enzymatic activity of glutamine-decarboxylase (Münzing and Bolling, 1985). The adverse effect of CO_2 on germination of rice, maize, and wheat becomes more pronounced at temperatures higher than 47°C and, this adverse effect may not be detectable at all below 30°C (Banks and Annis, 1990). Therefore, if preservation of germination is of primary importance, the use of CO_2-free, low-O_2 atmospheres is to be preferred.

Hermetic storage of seeds modifies the atmospheric composition surrounding them by depleting the O_2 through insect, mold, and seed respiration (Navarro et al., 2002). The atmosphere within the storage container therefore becomes insecticidal, fungistatic, or fungicidal. Moreno et al. (1988) showed that maize (corn) seeds stored at moisture contents between 15.3% and 17.7% were not invaded by fungi when stored under hermetic conditions and they maintained a higher viability than seeds with similar moisture contents not stored hermetically. Corn stored for 90 days at 15.3% moisture content maintained a viability of 95% under hermetic conditions, compared to viability that dropped to 43% in samples kept under nonhermetic conditions (Moreno et al., 1988).

Under the high humidity of the tropics, microflora commonly invade stored seeds (Mendoza et al., 1982). Therefore, the problems of maintaining seed viability in storage have always been an important concern to farmers and seed growers in the developing countries due to inadequate storage facilities. However, under hermetic storage conditions, storage insects can develop a storage atmosphere lethal to themselves before they cause damage to the germination of seeds. Flexible plastic structures suitable for long-term storage systems, as well as intermediate grain storage for cooperatives and subsistence farmers intended for the storage of grain in bags or in bulk, have been developed in Israel (Navarro et al., 1990). In certain situations, a complete hermetic seal cannot be achieved and a leak factor has to be taken into consideration. For this purpose predictive models have been developed to determine the response of insects to different gas-tightness levels (Navarro et al., 1994).

Viability of corn stored under hermetic (148 days' storage at 29 to 31°C) and nonhermetic (120 days storage at 28°C) conditions in the Philippines did not indicate significant changes between the initial and final samples. In the hermetic storage, the CO_2 level rapidly increased to 12% while the O_2 concentration sharply declined to around 7% over the first 2 weeks of storage (Navarro and Caliboso, 1996; Navarro et al., 1998c).

To test viability of paddy stored under hermetic and nonhermetic conditions, two trials were carried out in the Philippines, one lasting for 117 days and the other for 187 days (Navarro and Caliboso, 1996; Navarro et al., 1997b). Viability of paddy stored under hermetic conditions did not change significantly during the trials. Only a slight reduction was observed in the viability of paddy in the control. Similar tests carried out in Cambodia lasted for 223 days, during which period the increase in moisture content was from 13 to 14% in the hermetic and from 13 to 15% in the control stack. This significant increase apparently influenced the sharp decrease in viability of paddy in the control stack from 95% at the start of the trial to 66% at the end, whereas the hermetic seal preserved the germination capacity and the drop was only from 97% to 91% for the same period of time (Bunna, 2001).

To test viability of wheat stored under hermetic conditions in Israel, two trials were carried out with storage periods of 1440 and 450 days under hermetic conditions. In the first trial, the viability of wheat changed only slightly from the initial 99% to 97% at the end of 1440 days. In the second trial the viability of wheat dropped slightly from an initial level of 97% to 91%, at the end of the storage period. In both trials, insect populations were successfully controlled and the average CO_2 concentrations ranged between 10% and 15% (Navarro and Caliboso, 1996).

8.2.2.4.2 Product Quality Preservation

Data on comparative effects of low-O_2 and high-CO_2 atmospheres on quality parameters are very limited. Richard-Molard et al. (1987) state that generally, low-O_2 atmospheres preserve quality better than air, but there are some indications that CO_2-rich atmospheres should be checked for effect before use in unfamiliar conditions. For instance, Shejbal (1980) warns of (unspecified) detrimental effects on quality. Wheat held for long periods under unfavorable storage conditions and high-CO_2 atmospheres yields flour with a much longer mixing time than that stored under the same O_2 concentration in N_2 only. CO_2 was at one time suspected of causing increased yellowing in rice in storage, but laboratory studies suggest that this is not so (Banks and Annis, 1990).

Donahaye et al. (2001) reported on quality preservation of paddy stored in stacks of capacities ranging from 13.4 to 31.9 tonnes in flexible hermetic enclosures, placed outdoors for durations of 78 to 183 days in the Philippines. Quality of the paddy was compared with that of three control stacks (5.3–5.6 tonnes capacity) held under tarpaulins in the open for 78–117 days. The enclosures consisted of heavy-duty PVC-based sheeting sufficiently gas tight to control insect infestations. Initial and final samples were taken to determine changes in paddy quality, insect infestation, fungal infection, milling recovery, head rice, yellow kernels, and brokens. Germination and weight loss were analyzed. Percentage milling recovery and levels of yellowing in the gas-tight stacks showed no significant change. The two control stacks showed decrease in head rice and increase in brokens. Rice yellowing was very pronounced in one of the control stacks. These quality parameters indicated the significant advantages of the flexible hermetic enclosures under tropical climates.

8.2.2.5 Generation and Application of MA

At present, the most widely used source for production of MA gas compositions is tanker-delivered liquefied CO_2 or N_2. Availability and suitability of this means of gas supply must be questioned when the gases are transported over long distances from an industrial production area to the storage site. Therefore, alternative methods of generating MAs should also be considered.

8.2.2.5.1 Supply of Gases from Tankers

When the target MA gas composition is $< 1\%$ O_2 or high-CO_2 concentration, a commonly used method is to supply N_2 or CO_2 from pressurized tankers. A significant portion of the cost of applying MAs generated from tankers is for transportation and on-site purging. Bulk liquid gas is transported in conventionally insulated road tankers. For large-scale application of N_2 or CO_2, vaporizers are essential (Guiffre and Segal, 1984).

8.2.2.5.2 Exothermic Gas Generators

For on-site generation of MAs by combustion of hydrocarbon fuel to produce a low-O_2 atmosphere containing some CO_2, commercial installations (termed exothermic gas generators or gas burners) are available. Such equipment was originally designed for MA storage of fresh fruits. Their MA composition had been designed to allow the presence of approximately 2–3% O_2 (though now it is lower) and to remove CO_2 through scrubbers. Therefore, their use in the grain industry requires several adaptations, such as tuning the equipment to obtain an O_2 level of < 1%; utilization to full advantage of the CO_2 generated; and removal of excessive humidity from the atmosphere generated. Combustion of propane yields approximately 13% CO_2 and combustion of butane yields approximately 15% CO_2. Equipment has been designed to operate with open flame burners and catalytic burners, and as internal combustion systems. Full-scale field trials using open flame burners (exothermic MA generators) (Storey, 1973; Fleurat-Lessard and Le Torc'h, 1987) and catalytic burners (Navarro et al., 1979) to provide a low-O_2 gas mixture have proved successful.

8.2.2.5.3 On-site N_2 Generators

Commercial equipment using the process of O_2 adsorption from compressed air passed through a molecular sieve bed, also termed "pressure-swing adsorption" systems, is available (Zanon, 1980). For continuous operation a set of two adsorbers is provided, which operate sequentially for O_2 adsorption and regeneration. Nitrogen at a purity of 99.9% can be obtained through regulation of inlet air flow. This method of N_2 generation is a relatively new approach in MA generation technology. Equipment is now being manufactured that is rated to supply an outlet flow rate of 120 m^3/h at an outlet purity of 98% N_2. However, in view of the high capital cost investment involved, it would seem wise to undertake a long-term cost–benefit analysis to explore the justification of usage of these installations.

8.2.2.5.4 Biogeneration of MAs

Two principal forms of biogeneration of MAs are considered, namely "hermetic storage" and "assisted hermetic storage."

Hermetic storage: A high level of gas-tightness is required for a structure to be suitable for hermetic storage of dry grain. Hermetic storage in flexible plastic storage systems, under subtropical climatic conditions, continues to offer an excellent solution, provided there is a certain degree of tolerance to the presence of live insects at critical places in the storage structure, particularly at the grain surface, where moisture condensation is likely to occur. At the end of long-term hermetic storage, when unloaded grain is destined for immediate consumption, the risk of spreading insect infestation was found to be negligible. Insect control success due to the hermetic storage treatments is comparable to conventional fumigants (over 99.9% kill), and losses due to insect activity are minimal (0.15% loss in weight for a storage period of 15 months) (Navarro et al., 1984; Varnava, 2002).

Assisted hermetic storage: The term "assisted hermetic storage" was introduced by Banks (1984) in order to define a process in which MA generation is assisted by a biogenerator source without sacrificing the commodity. Using a similar approach, Calderon et al. (1981) examined the possibility of generating a MA by inoculating wet rice bran with storage molds. The best-known working example of assisted hermetic storage is that in use in China (Lu, 1984). With this method, removal of O_2 is achieved by recirculating storage gases through a closed system containing racks of moist grain and bran infected with a particular mold culture.

8.2.2.5.4.1 Factors Affecting Insect Mortality in Hermetic Storage

The important role of low-O_2 concentration rather than high CO_2 in causing mortality of stored-product insects in hermetic storage was demonstrated by Bailey (1965). To evaluate the effects of incomplete air tightness Navarro et al. (1994) modeled a fixed O_2 ingress rate equivalent to about 0.24%/day for a structure with a volume of 10 m^3. For these given values, changes in oxygen concentrations in response to the respiration of different initial insect populations are illustrated in Figure 8.6. Accordingly, a cyclic change in concentrations is obtained as a result of O_2 ingress and the ability of insects to survive at low O_2 levels. These theoretical cyclic changes in O_2 concentrations are also observed in different laboratory and field studies. The amplitude of these cyclic changes is dependent on the level of initial infestation and the permeability of the membrane and the level of air tightness that dictate the rate of O_2 ingress rate into the sealed system (Navarro et al., 1994).

The influence of temperature on insect respiration implies that in warm climates O_2 intake by insects is very intensive. Conversely in temperate climates, insect metabolism is much slower, depletion of O_2 may be slower than its ingress, and insect control may not be achieved. This led Burrell (1980) to postulate that for light infestations of cool grain, residual populations would provide an inoculum for reinfestation after the grain is removed from hermetic storage.

8.2.2.5.4.2 Modern-Day Hermetic Storage

In the early 1970s, above-ground structures were designed in England for emergency storage using flexible plastic liners supported by a welded mesh frame. These liners

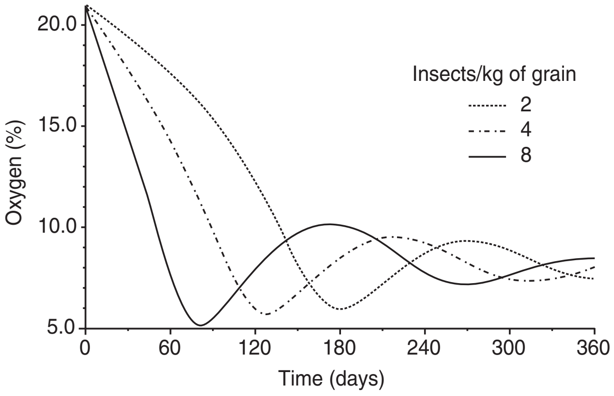

FIGURE 8.6 Calculated oxygen concentrations in a 10-m^3 grain mass containing different infestation levels of insects having an oxygen intake of 157 (μL/insect)/day using a sealed liner with an oxygen ingress rate of 0.24%/day. (From Navarro et al., 1994.)

were made of butyl rubber, sometimes laminated with white Ethylene Propylene Diene Monomer (EPDM), and consisted either of a wall-floor section plus a roof section attached after loading, or both sections welded into a single unit (Kenneford and O'Dowd, 1981). However, under tropical and subtropical climates the liners were found to deteriorate (Navarro and Donahaye, 1976; O'Dowd and Kenneford, 1982).

In Israel, the manufacture of PVC liners that conform to prerequisite specifications of durability to climate, gas permeability, and physical properties enabled the development of four storage systems based on the hermetic principle. These are:

1. Bunker storage for conservation of large bulks of 10,000 to 15,000 tonnes capacity (Navarro et al., 1993).
2. Flexible silos supported by a welded mesh frame of 50–1000 tonnes capacity for storage of grain in bulk or in bags (Calderon et al., 1989; Navarro et al., 1990).
3. Liners for enclosing stacks of 10–50 tonnes capacity termed storage cubes, and designed for storage at the farmer-cooperative and small trader level (Donahaye et al., 1991a). These structures are in current use for capacities of up to 300 tonnes for bagged storage of cereals (Figure 8.7).
4. Liners of 600- to 1200-kg capacity equipped with upper in-loading and lower out-loading sleeves and placed inside a rigid cylindrical protective wall for small-scale farmers in the tropics. These structures are placed on locally made platforms and protected with straw roofs and strongly resemble traditional storage silos (Navarro et al., 1999).

The problem of applying present-day technologies to provide hermetic storage for subsistence farmers lies in the need to provide an easily sealable low-cost container of 50–100 kg capacity. The high surface-area-to-volume ratio necessitates a liner with a very low permeability to gases. The most recent attempt to address

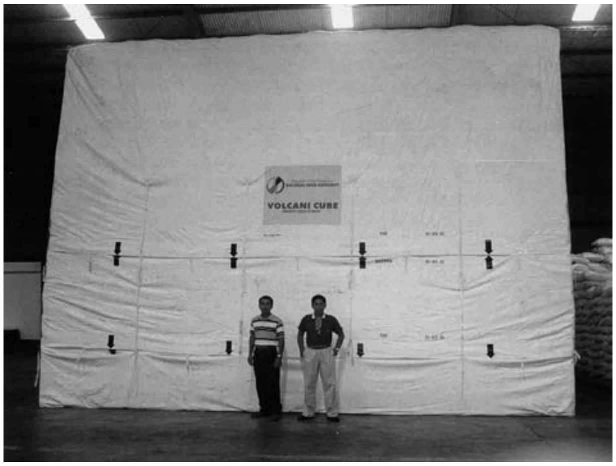

FIGURE 8.7 Hermetic storage of paddy in bags using Volcani Cube (GrainPro Cocoons) of 300 tonnes capacity at the National Food Authorities warehouse in the Philippines.

this problem has been through the “Joseph bag,” which is made of a plastic–metal foil laminate, sealable by means of a hot iron (Murray, 1990). Also recently a transparent multilayer with gas barrier for storage of cereals up to 50 kg capacity under the name of SuperBag™ has been proposed for sealed storage (Tom deBruin, personal communication, 2004).

8.2.2.5.4.3 Hermetic Storage as a Future Alternative

The use of modern and safer acceptable technologies such as refrigerated aeration and modified atmospheres are still expensive and require adequate infrastructure. In sharp contrast to the use of chemicals, hermetic storage is an environmentally friendly technology, involving no hazard to the storage operators, consumers, or nontarget organisms, and as such, its application should enjoy a high level of consumer acceptance.

8.2.2.5.4.3.1 In Developing Countries

Hermetic storage may provide an answer to the need for a less costly method of storage for food security of the rural populations. This could be achieved by supplying a storage solution at the farmer level, and thereby affording the farmer protection from seasonal fluctuations in grain prices. The basic advantage of hermetic storage in developing countries is its simplicity, obviating the need for expensive insecticidal admixture procedures or fumigations, both of which require high levels of expertise not usually possessed by the small-scale farmer. Furthermore, it is generally the only MA option since MA generators or gas cylinders are neither affordable nor obtainable.

8.2.2.5.4.3.2 In Technologically Advanced Countries

The conversion of rigid structures to sealed storages should be considered for long-term large-scale storage projects. The evidence that this method is most effective at the high temperature prevailing in hot climates is best documented by De Lima (1990). In tropical climates, aeration for cooling of grain is not feasible, reinfestation is frequent, and the available contact insecticides degrade rapidly because of high temperatures. Under these conditions hermetic storage may provide an advantageous solution.

8.2.2.5.5 High-Pressure Carbon Dioxide Treatment (HPCT)

Carbon dioxide still remains slower acting and more expensive than phosphine or methyl bromide. To address this problem, the stored-product pests laboratories at Bordeaux and Berlin have investigated the use of carbon dioxide at high pressure (Fleurat-Lessard, 1990; Reichmuth and Wohlgemuth, 1994). After extensive testing in the laboratory, a high-pressure fumigation chamber was designed and built in collaboration with MG SIAC (France). The chamber can hold the equivalent of the contents of one transport trailer. The unit is designed to recover at least 85% of the carbon dioxide used. The pressure rises to 19 atmospheres in 90 minutes, is held there for 60 minutes, and takes about 30 minutes to release the pressure. With loading, fumigation, and unloading, a full cycle takes approximately 4 hours.

Prozell et al. (1997) described a high-pressure chamber (CARVEX) connected to a tank of liquid CO_2 placed on a balance. This unit is commercially available and utilized in Germany.

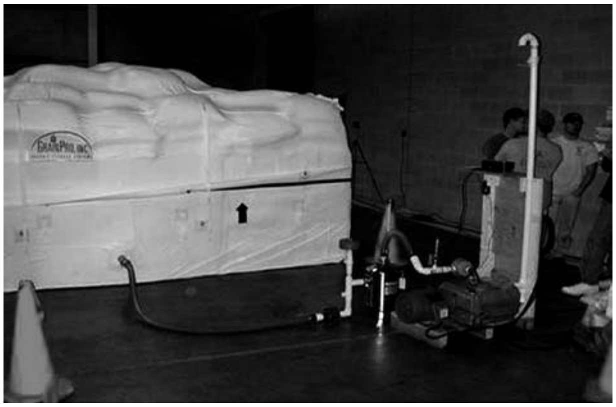

FIGURE 8.8 A V-HF Cocoon holding cocoa beans in bags, under a pressure of 50 mm Hg connected to the vacuum pump in a trial site in Boston, MA.

8.2.2.5.6 Low-Pressure (V-HF)

Finkelman et al. (2003a) reported on the introduction of flexible transportable sealed chambers made of welded PVC liners that has opened new opportunities to implement low pressures (vacuum treatment) as a competitive and affordable treatment to control storage insect pests. Under vacuum, these chambers shrink over the periphery of the commodity and hold it fast. The system is sealed by an airtight zipper and is able to retain vacuum (Figure 8.8).

Finkelman et al. (2003a) showed that it is not a practical approach to attempt to hold a pressure below 45 mm Hg because of the energy required for prolonged operation of the pump. Conversely, pressures above 55 mm Hg prolong the time to achieve kill.

Durable commodities (corn, corn chips, garden peas, chick peas, wheat, wheat flour, rice, sunflowers seeds, and semolina) packed in different ways were exposed to 5 days' vacuum treatment. In all tested commodities the treated product was well preserved, and in cases where initial infestation was detected, complete mortality of insects was observed. The advantage of this treatment is that no toxic chemicals are employed. In comparison with phosphine, exposure times to provide kill are similar and the exposure time of 5 days falls within a range suitable for quarantine treatments where no rapid treatment is essential. The application of vacuum in cocoons made of flexible liners as a treatment of durable commodities that can withstand the low pressures is now being implemented by commercial companies.

8.2.2.6 Specific Applications of MA

8.2.2.6.1 Cereal Grain Preservation

The initial research carried out during recent decades concentrated first on the possible application of the MA technology to cereal grains (Jay, 1984a; Banks and Annis, 1990; Adler et al., 2000; Navarro et al., 1990). Additional studies relating to the preservation of cereal grain are well documented in the book of Calderon and Barkai-Golan (1990) and the chapter of Adler et al. (2000).

8.2.2.6.2 Tree Nuts and Dried Fruits Preservation

The possibility of applying MAs to control insects in dried fruits and tree nuts has been reviewed by Soderstrom and Brandl (1990). The major volume of MA treatments relates to the finished, packaged product. Bulk storages require extensive sealing before MA can be applied, and the industry considers the process too slow and costly in comparison to other control methods. The influence of low-O_2 or high-CO_2 atmospheres as alternatives to fumigation of dried fruits has also been investigated by Soderstrom and Brandl (1984), Soderstrom et al. (1986), and Tarr et al. (1994).

Ferizli and Emekci (2000) applied CO_2 for treating dried figs in a gas-tight flexible storage unit loaded with 2.5 tonnes of dried figs in perforated plastic boxes. Results showed that O_2 concentrations in the containers decreased to 0.8% and CO_2 concentrations increased to 96%. For the following 5 days both O_2 and CO_2 concentrations remained stable. These conditions resulted in complete mortality of both insects and mites.

Prozell et al. (1997) exposed cocoa beans, hazel nuts, and tobacco to a quick disinfestation process of exposure to carbon dioxide under pressure of 20–40 bars for a few hours. Experiments with caged insects (developmental stages and adults) of 12 species were carried out on 1 tonne of bagged products in a 3-m^3 chamber. At about 10°C and at 20 bar of CO_2 the lethal treatment period was 3 hours longer than at 20°C. At 20°C and 30 and 37 bars, complete control was achieved within 1 hour and within 20 minutes, respectively.

8.2.2.6.3 Disinfestation of Dates

As a potential alternative to methyl bromide fumigation, the influence of different CAs in causing emigration of *Carpophilus* spp. larvae from dates was compared with that of methyl bromide by Navarro et al. (1989) and Donahaye et al. (1991b). A concentration of 35% CO_2 was found to cause a similar emigration to methyl bromide. This method was used for several years in the largest packing house in Israel.

More recently laboratory experiments were carried out to investigate the influence of different modified atmospheres (20% CO_2 in air or 2.8% O_2 in N_2), low pressures alone, or methyl bromide alone in causing nitidulid beetles to emigrate from infested dates (Navarro et al., 1993; 1998a). At 4 hours exposure and at 26ºC, the treatments that had a marked influence in causing insects to abandon the infested dates were a low pressure of 100 mm Hg and 2.8% O_2 in N_2, both of which caused over 80% of the initial insect populations to emigrate from the fruit. In addition to causing emigration of nitidulid beetles from dates, CO_2 atmospheres were studied for long-term preservation of the dates. Under laboratory conditions (Navarro et al., 1989) and in field tests at ambient temperatures, Navarro et al. (1998b) showed that carbon dioxide significantly delayed browning and sugar formation in dates and extended shelf-life as compared to storage at –18°C.

8.2.2.6.4 Packaging of Food

Lang (1993) discussed the use of atmospheric gases in the packaging of meat and fish, milk products, bakery products, fruit, vegetables, and nuts.

The effects of storage temperature (8^o and 36°C) and packaging atmosphere (air and N_2) on the quality of almonds were studied by Garcia-Pascual et al. (2003). The quality of unshelled almonds remained high after 9 months, even under storage at ambient temperature. No significant differences were observed for any of the measured parameters in nuts stored in air or N_2.

Guidelines for using modified atmospheres in packaged food, with special emphasis on microbiological and nutritional aspects, have been published by the Council of Europe (Anonymous, 1999).

8.2.2.6.5 Fresh Storage of Fruits and Vegetables

Fresh fruits and vegetables may be shipped or stored in controlled atmospheres. This topic is covered in depth in the book of Calderon and Barkai-Golan (1990) and in a special chapter of the current book *Modified Atmosphere Packaging and Controlled Atmosphere Storage* by Ben-Yehoshua, Beaudry, Fishman, Jayanty, and Mir.

8.2.2.6.6 Narcissus Bulbs Treatments

The large narcissus fly *Merodon eques* F. attacks narcissus bulbs and also bulbs of other geophytes. This species is a quarantine pest that demands total mortality prior to export from Israel (Donahaye et al., 1997b). Fumigation with methyl bromide has been used to eliminate narcissus fly infestation in flower bulbs due to its rapid killing time (4 hours). However, methyl bromide is also known for its phytotoxic effect on the bulbs, and it will be phased out for nonquarantine purposes by 2005 in developed countries.

In experimental procedures, Navarro et al. (1997a) found that there was an extremely rapid depletion of O_2 within the sealed gas-tight enclosure where the bulbs were stored due to the respiration of the newly harvested narcissus bulbs. This procedure also revealed the significant anoxia achieved within less than 20 hours (less than 0.1% O_2 and about 15% CO_2) during treatment at 28 to 30°C and the possibility of using it alone as a control measure (Rindner et al., 2003). The possibility of obtaining a bio-generated modified atmosphere utilizing the bulb respiration alone was adopted by the farmers as a practical solution using specially designed flexible treatment chambers (Figure 8.9). The larger narcissus bulb larvae were controlled on all 13 treatments carried out during the 2003 export season (Navarro et al., 2003b).

FIGURE 8.9 Narcissus bulbs in standard boxes before loading on pallets (upper left), loading the pallets containing the narcissus bulbs (left), and the general view of two sealed V-HF Cocoons under treatment.

8.2.3 INERT DUSTS

Inert dusts, such as ash, lime, various ground minerals, and clays, have a long history of use for grain protection. Banks and Fields (1995) and Subramanyam and Roesli (2000) detailed the various aspects of the use of inert dusts as an alternative to chemical pesticides in stored products and for inclusion in IPM programs.

Banks and Fields (1995) categorized the inert dusts into four basic types:

1. Clays, sands, and ash (paddy husk ash or wood ash).
2. Dusts that contain natural silica such as diatomaceous earth (DE) that are obtained from diatoms deposited on earth. These are the fossilized remains of diatoms –(microscopic, unicellular, aquatic plants) that have a fine shell made of amorphous hydrated silica.
3. Synthetic silica or silica gels that are produced by drying an aqueous solution of sodium silicate.
4. Mineral dusts such as dolomite, magnesite, copper oxychloride, lime (calcium hydroxide), limestone (calcium carbonate), and tricalcium phosphate, which have been shown to be effective in controlling insects.

The main mode of action for inert dusts is assumed to be desiccation due to water loss through abrasion of the cuticle. Other possible causes considered by researchers were blocking the spiracles, thereby causing the insects to die from asphyxiation; absorption of water from the insect's cuticle; ingestion of the dust particles; and absorption of the epicuticular lipids of insects leading to excessive water loss through the cuticle. Recently Prasantha et al. (2003) investigated the effects of DE on the physiology of the cowpea weevil. They argued that death of the weevils could be a result of high water loss together with stress-related high physiological metabolic activity.

There are advantages and limitations to applying inert dusts. The most widely used inert dusts are the DE dusts that are now becoming commercially acceptable by the grain and food industry. Fields (2000) described some of their advantages and limitations in detail.

Among the main advantages of using inert dusts, and particularly DEs, are their low mammalian toxicity (for rats the oral LD_{50} > 5000 mg/kg of body weight) (Subramanyam et al., 1994). They are stable on the grain and provide protection as long as the dusts remain dry. Inert dusts do not leave toxic residues. The new DE formulations do not affect the milling, baking, and malting properties of treated grains (Korunic et al., 1996). DE dusts can be applied to empty facilities as well as to grain as dry powders. To reduce worker exposure to the dusts some DE formulations can be applied as slurry. Inert dusts are ovicidal (El Halfawy et al., 1977), and such an action may be of value when they are applied as a surface treatment to empty storage facilities, warehouses, and mills.

Among the main limitations of using inert dusts and particularly DEs are the safety and the regulatory issues. These issues were reviewed by Korunic (1998) and Desmarchelier and Allen (2000). Although DE and synthetic silicas are amorphous dusts, they contain < 1 to 4% crystalline silica. Therefore, there is concern about worker or consumer exposure to silica dusts, primarily through inhalation. Silicosis is an irreversible lung disease in which fibrous tissue is formed as a reactive response to inhaling silica dust.

In addition, there are several objections related to the use of inert dusts, such as the increase in the angle of repose of treated wheat, the decrease in flowability, damage to machinery, and reduced grain bulk density or test weight.

The application with these dusts should be made under environmental conditions in which the dusts perform best. It is clear from tests conducted under laboratory conditions that the minimum effective rate of dust needed for suppression of progeny production of several species of beetles and moths is about 50% less than that needed to produce complete mortality (Desmarchelier and Dines, 1987; Subramanyam and Roesli, 2000). Therefore, these minimum effective rates should be used for testing under field conditions.

8.2.4 IMPACT AND REMOVAL

Physical disturbances such as rotation, tumbling, and especially impact of infested granular commodities adversely affect stored-product insects. The limited application of these physical measures remains restricted to the impact machines that are ideal for insect control in the semolina and flour industry. Banks and Fields (1995) and Plarre and Reichmuth (2000) provided detailed review on the subject.

Regular turning of grain from one bin to another could be lethal to insects, and suppression of insect populations could be achieved by allowing time for more tolerant stages to develop into more susceptible stages and then turning the grain again. Modern field studies investigating the direct effect of shock on insect pests are restricted to the work of Bahr (1991). He showed that some species were particularly susceptible to damage during pneumatic conveyance of grain. Physical removal of pests from grain and grain storages can be accomplished by sieving the grain and by various forms of cleaning in grain stores. However, apart from cleaning purposes, physical removal as a control process has not gained recognition as an effective control measure in the modern food industry.

Impact machines are centrifugal in action and essentially consist of two spinning disks equipped with and connected by a different number of steel pegs towards the edge of the disks, making them function as a single rotor. Originally, impact machines or pin mills were used for additional reduction of product particles passing through the milling process, thus reducing the overall production and energy costs (Marriott, 1999). They were invented during the 1940s and were named entoleters (Grobe, 1957).

The commodity (whole cereal grain, coarse particles, or flour) is fed into the center of the entoleter between the disks and then accelerated outward by the inflow generated by the disks' rotation. The commodity hits the steel pegs and also the machine casing at high speed. Typically, the pegs are arranged in two or more rows, and the outer row is slightly offset from the inner row. Generally, insect mortality increases with increasing velocity of the steel pegs, but decreases with increasing throughput rates of the commodity. Bailey (1962) found that about 90% of adult *S. granarius* were killed when infested wheat was impacted at 25 m per sec. Eggs and especially the younger larvae of these weevils are protected inside the kernels and survive impact at velocities of 45 m per sec (Bailey, 1962). Insects in semolina, flour, and grain dust are more susceptible than insects inside kernels (Stratil et al., 1987). It is believed that the hard and sharp edges of semolina particles cause abrasion of the insect's cuticular wax layer, leading to death by desiccation. Flour and grain dust particles are smoother, and therefore, this effect is less evident.

The use of impact machines should be economical. Low throughput rates sometimes slow down the milling process. For this reason the practice of by-passing impact machines is not uncommon. Larger impact machines with higher capacities that guarantee complete kill of pest insects are needed by the grain and food industry.

8.2.5 RADIATION

8.2.5.1 Nonionizing Radiation

For the treatment of stored-product commodities, nonionizing radiation is considered benign compared to ionizing radiation. Table 8.4 lists a comparison between different types of radiation.

An effective way of controlling storage insects is to elevate their body temperature to between 45 and 60°C using microwave energy. The application of radiation at frequencies in the electromagnetic spectrum is limited to the treatment of products where the water content of the product is much less than that of the insect. This ensures that the insect may be heated selectively and that the quality of the product itself is unaffected by excessive heating. Dry stored products and particularly cereal grains are, therefore, the most likely to benefit from this treatment, since their moisture content is below the equilibrium relative humidity of 70%. Nelson (1996) and Nelson et al. (1997) showed that selective heating of the insect was greater at operating frequencies between 10 and 100 megahertz than at 2.45 gigahertz. However, there is currently no dielectric heating equipment available at 39 megahertz with sufficient output power to treat a product at a high throughput rate. Furthermore,

TABLE 8.4
Microwave Energy in Comparison With Other Electromagnetic Energy

Radiation Type	Typical Frequency (Megahertz)	Quantum Energy (Electron Volts)
Gamma ray	3.0×10^{14}	1.24×10^{6}
X-ray	3.0×10^{13}	1.24×10^{5}
Ultraviolet	1.0×10^{9}	4.1
Visible	6.0×10^{8}	2.5
Infrared	3.0×10^{6}	0.012
Microwave	2450	0.0016
Radio	1.0	4.0×10^{-9}

Source: From Kingston et al., 1997.

bioassay information on all development stages, including eggs, young larvae, old larvae, pupae, and adults, to achieve a > 99% kill at that frequency is needed (Halverson and Nablo, 2000).

A system capable of generating 250 kilowatts at 28 gigahertz, employing the VGA-8000TM gyrotron built by Communication and Power Industries, Palo Alto, CA, that has the potential to treat soft white and hard red wheat at a throughput rate of 54.4 metric tonnes per hour, was reported by Halverson and Nablo (2000). Recently Sanchez-Hernández et al. (2002) described the use of a preindustrial microwave applicator for the disinfestation of rice. The applicator is a patent-protected modular system designed for continuous treatment.

8.2.5.2 Ionizing Radiation

The potential application of ionizing radiation in agriculture, and in particular for the treatment of storage insects, was considered with enthusiasm some 30–40 years ago. This enthusiasm continued until analysis showed the economic impracticability and safety concerns related to its use for large-volume disinfestation of durable agricultural products. Urbain (1986), Tilton and Brower (1987), and Watters (1991) published extensively on the radio-sensitivity of stored-product pests. The two types of ionizing irradiation considered for insect control in grain were γ-radiation produced from CO^{60} or Cs^{137} sources and accelerated electrons. Bull and Cornwell (1966) and Adem et al. (1978) found γ-irradiation to be more effective for the same dosage than accelerated electrons. The higher energy γ-irradiation penetrates at least ten times as far into solid foods as does electron-beam irradiation (Anderson, 1989), thus grain must be in shallow layers during electron beam irradiation.

The basic unit used in ionizing radiation is a dose that is of specific energy absorption or energy absorbed per unit mass. The international unit is the Gray, which is equivalent to 100 rad (radiation absorption unit). A widely used unit is the kiloGray (kGy), which is 1000 Grays. Microbiological applications of ionizing radiation employ the megarad, which translates to 10 kiloGrays. Entomological studies involve much lower doses, typically in the range of hundreds of Grays. Therefore, the energy used for radiation is a fraction of a Joule per kilogram of product for disinfestation. Since a kilowatt-hour of electrical energy is 3.6×10^6 Joules, this permits us to assess that the basic energy costs are not a problem for disinfestation purposes, and there should not be any concern about temperature elevation of the product. Radiation processes up to sterilization levels are commonly considered “room temperature” processes (Halverson and Nablo, 2000).

Irradiation at 10 kGy is regarded as the safe upper limit of toxins production in treated foods. The World Health Organization recommends that foods treated at this or lower doses be exempt from toxicological testing (Urbain, 1986). At lower dosages of 3–5 kGy that cause death of stored-product pests within 24 hours, there can be significant damage to the processing quality of wheat and other cereals. Irradiation can reduce vitamins A, C, E, B1 (thiamin), and K. The amount of reduction is dependent on the food irradiated, the dose, and other factors (Urbain, 1986). Bread quality was affected only after wheat was irradiated at doses above 2.5 kGy (Lee, 1959), but some starch damage may be apparent at 0.5 kGy (Ng et al., 1989).

Studies were carried out to determine the dosages required for death after several weeks, and for sterilization. These are typically between 0.2 and 0.5 kGy for beetles and mite pests, but more than 1.0 kGy for moths (Banks and Fields, 1995). At 0.5 kGy, beetles and the immature forms of mites and moth pests are sterilized, but some adult moths may remain fertile. The few progeny they produce, however, will be sterile due to inherited genetic damage (Tilton and Brower, 1987). The doses of irradiation needed to kill insects can also affect germination, making this type of control unsuitable for malting barley (Watters and MacQueen, 1967) or seed stocks.

Disinfestation of bulk grain by radiation has been technically feasible for several decades, but its full-scale routine use is limited to a number of pilot facilities established over the past 25 years for the study and optimization of the disinfestation process. One of the earliest was described by Adem et al. (1981) located at the Institute of Physics, National University of Mexico. An electron beam for grain disinfestation has operated at the Port of Odessa in the Ukraine. A schematic description of this installation was first reported in 1981 (Zakladnoy et al., 1982, 1989). An electron beam fluidized-bed processor has been developed by Nablo et al. (1998) at Electron Processing Systems in North Billerica, MA.

In the United States, both the gamma and electron beam service irradiators are currently used for microorganism control. The existing federally established dose limit for arthropod pests in grain is 1 kiloGray (Anonymous, 1996).

A detailed study of the economics of insect disinfestation by irradiation has been published by Lapidot et al. (1991) for both γ-ray and electron beam sources. Economic analyses published in 1975 by Radiation Dynamics (Cleland, 1975; Watters, 1979) for a 200-tons-per-hour accelerator system gave comparable costs ($0.17 per ton). The profound impact of scaling up on processing costs is evident, although adjustment of Lapidot et al. (1991) data to a 1-kiloGray treatment level elevates cost by about $1.00 per tonne. For purposes of reference, 1995 chemical fumigation costs in the United States were cited at $0.67 per tonne for large storage elevators (Hagstrum and Flinn, 1995).

8.3 USE OF PHEROMONES AND TRAPS FOR MONITORING INSECT POPULATIONS

In sharp contrast to the application of physically based technologies that to a large extent may affect the commodity, the microflora, and the insects, the use of pheromones and traps relate directly to insects only. Pheromones are chemical signals (semichemicals) used between insects or mites of the same species for various purposes. There are various types of pheromones; sex pheromones and aggregation pheromones are the most commonly studied. Sex pheromones are released by insects of one sex to attract insects of the opposite sex for mating. Aggregation pheromones are typically released by one sex and attract males and females to locations where mating occurs and where females find oviposition sites on appropriate larval food substrates.

To date, sex pheromones, used in mate-finding, have proven to be the most effective in pest management, particularly as a monitoring tool. This is probably due to their very low response thresholds and extreme specificity, which permits the targeting of one species without effect on the rest of the storage ecosystem.

Pheromones are compounds of low molecular weight of approximately 100–200 atomic mass units; they are volatile, usually oxygenated, organic compounds with straight-chain, branched, or ring structure, with or without double bonds. A key feature of pheromones is that a very small amount of pheromone, estimated to be as little as a few molecules on contact with the antennae, can elicit a behavioral response in a nonspecific receiver. Phillips et al. (2000) listed 40 species of stored-product insects for which pheromones have been identified, and among them 22 are those for which synthetic pheromones or formulated pheromone lures are commercially available.

8.3.1 Monitoring Pests with Attractants

8.3.1.1 Pheromone Lures and Traps

A variety of traps baited with synthetic pheromones have been developed for use in monitoring programs in food processing and storage facilities (Figure 8.10). The slow release of pheromone from lures is achieved by incorporating the compound into a plastic matrix, from which it is slowly released during several weeks or months. The most common trap design for flying insects employs plastic or wax-coated paper covered with insect-trapping glue on one or more surfaces (Figure 8.10B). Sticky traps have been used almost exclusively for monitoring storage moths, but they have a relatively short service life because they are made of paper. Bucket and funnel traps made of durable plastic construction (Figure 8.10A) can be used for flying insects and are considered both nonsaturating, due to their large collection reservoirs, and reusable.

8.3.1.2 Grain Probe Traps

Grain probe traps or pitfall-cone traps are placed at or below the surface of grain masses and do not require the use of pheromones (Figure 8.10C). These traps capture beetles that are simply walking through the holes of the probe shaft, drop through the void inside the probe, and are directed by a funnel into a collection vial (Barak

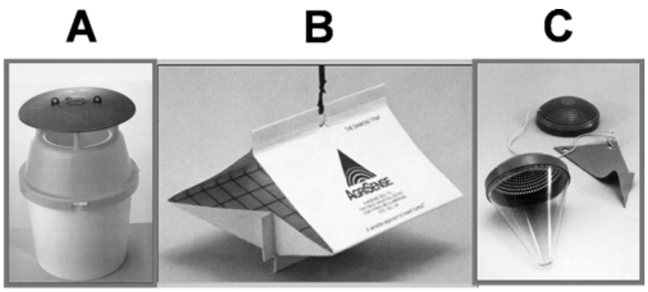

FIGURE 8.10 Monitoring equipment: bucket trap for flying insects with pheromone lure (A); diamond-shaped sticky trap (B); and pitfall-cone trap for grain insects (C).

et al., 1990). They are important tools in detecting the presence of beetles' populations in grain masses at densities lower than those that can be detected by regular sampling of the grain and examining for their presence (Hagstrum et al., 1990, 1998). A more recently developed technology for monitoring insects is a probe trap equipped with an electronic device to count insects that relay the counts to a computer (Shuman et al., 1996; Litzkow et al., 1997).

To determine the effectiveness of attractants in probe traps, Navarro (unpublished data, 1992) installed shelled and unshelled peanuts in traps in a pilot plant experiment; no significant differences were observed in the presence of the *Tribolium castaneum* aggregation pheromone attractants in the probes. Also according to Phillips et al. (2000), there is some evidence suggesting that pheromones and food attractants should not be used in devices intended for monitoring insects in bulk-stored grain.

8.3.2 SUPPRESSING PEST POPULATIONS WITH PHEROMONES

The idea of trapping all the insects in a population using sex pheromones, thereby causing it to be suppressed, has been proposed for various agricultural systems by Lanier (1990). For aggregation pheromones that attract females, mass trapping may have a significant impact on a population if substantial numbers of females are removed. For sex pheromones that attract only males, a critical number of males must be removed to ensure that an effective number of females go unmated. Several studies report successful population suppression of storage moths following deployment of a high density of traps (Levinson and Levinson, 1979; Süss and Trematerra, 1987; Trematerra and Battaini, 1987; Trematerra, 1988, 1991), but typically no evaluations of the success of the treatments were conducted other than continued monitoring with pheromone traps. Pierce (1999) reported on long-term mass trapping of *L. serricorne*, using sex pheromone in a commercial bakery over a 9-year period, and inferred population suppression from reduced trap catches. Such field studies are difficult to validate because of the lack of proper controls.

Another method for population suppression is mating disruption, in which the atmosphere of the pest's environment is saturated with a synthetic pheromone. Males are unable to locate and mate with females due to the saturated pheromone levels; unmated females do not reproduce; and the population declines in the next generation (Jones, 1998a, 1998b). Nearly all mating disruption research and application has been done with moths.

8.3.3 CURRENT USAGE

The main use of pheromones of stored-product insects remains as a tool for monitoring and detecting these insects by the food industry. On the other hand, no data were encountered of any commercial use of pheromones to control populations of stored-product pests using mass trapping (lure-and-kill) or mating disruption.

Even though probe traps have not been widely adopted by the grain industry, they are among the most sensitive methods to detect insect pests in bulk-stored grain. Among factors responsible for the disinterest in probe traps by the grain industry is the fact that most commercial grain managers are reluctant or forbidden to enter bulk storage structures or have workers walk on the surface of the grain because of safety concerns. An alternative developed recently is the use of electronic grain probe insect counter (EGPIC) (Shuman et al., 1996; Litzkow et al., 1997). Commercial development of EGPIC is presently under way, coupling EGPIC units together with temperature cables permanently installed in grain storage facilities.

8.3.4 RESEARCH NEEDS

The male-elimination methods of mass trapping, mating disruption, and lure-and-kill that have been researched with storage moths need to be rigorously evaluated in commercial settings and further developed into usable technologies. Phytoextracts are known that have repellent effects on storage insects. These repellents may disrupt colonization of insects in breeding sites and disrupt orientation of beetles towards food attractants. Preliminary data along this line were obtained for *R. dominica* (Phillips, 1998). A “push-pull” system could be developed to divert insects to traps or poison bait stations that are releasing attractants.

8.4 BOTANICALS

Many plants inherently produce various chemicals that protect them against insects, and extracts from these plants may affect the metabolism of insect species other than those attacking the plant from which the chemical was derived. Allomones are interspecific defensive chemical messengers that function as repellents or feeding deterrents. Plant secondary metabolites that deter oviposition or feeding by phytophagous insects belong to this category. A novel approach to pest management in food industries has been to harbor the potential powers of such semiochemicals (Phillips, 1997; Jones, 1998a; Agelopoulos et al., 1999; Phillips et al., 2000; Throne et al., 2000; Weaver and Subramanyam, 2000; Cox, 2004).

From the historical viewpoint the utilization of plant materials to protect field crops and stored commodities against insect attack has a long record. Many of the plant species concerned have also been used in traditional medicine by local communities and have been collected from the field or specifically cultivated for these purposes. Leaves, roots, twigs, and flowers have been admixed, as protectants, with various commodities in different parts of the world, particularly in India, China, and Africa.

In a recent review, Weaver and Subramanyam (2000) list a compilation of plant species used against stored-product insects in the laboratory and under subsistence conditions, this list having been compiled from citations in Prakash and Rao (1997).

8.4.1 CURRENT USAGE

8.4.1.1 Use in Subsistence Agriculture

Over the last 30 years, intensive and pioneering research has been conducted on various plant materials including neem and its derivatives, turmeric and the like. As a consequence, the potential role of botanicals in the fields of antifeedants, repellents, toxicants, and growth regulators has been established (Islam, 1987; Cox, 2004; Hou et al., 2004). Numerous plant substances have been isolated and tested on stored-product insects, and from among these, azadirachtin (extracted from neem) appears particularly promising as a potential stored-product protectant (Subramanyam and Hagstrum, 1995). Also, the mixing of neem extracts with other materials can boost their power. Among these so-called “promoters” are sesame oil and piperonyl butoxide (Anonymous, 1992).

Edible oils are locally used to prevent stored grains from insect attack in many countries in Asia and Africa (Shaaya et al., 1997). Most uses involve adding botanical preparations to commodities stored in the house, where addition of these preparations has been most effective against the pulse weevils or *Bruchidae*. Among admixtures used under similar circumstances, the following powders have been reportedly used: citrus peels, *Chrysanthemum* flowers, tobacco leaves, pepper fruits and seeds, neem leaves and seed portions, mint leaves, and marigold root powders, to name a few (Prakash and Rao, 1997).

It has also been an age-old practice in rural India to mix dried neem leaves and turmeric powder with stored grain or to place them among warm clothes to keep away insects (Jotwani and Srivastava, 1981; Koul, 1992). In some traditional storage practices, neem leaves are mixed with grain in storage for 3–6 months (Anonymous, 1992). Azadirachtin, alcoholic and aqueous extracts of neem seeds, and enriched formulations have revealed virtually no oral or dermal toxicity to mammals according to tests carried out so far. Neem flowers and leaves are even eaten as a vegetable in India, Burma, and Thailand (Schmutterer, 1988).

8.4.1.2 Use in the Food Processing Industry

At this time the only botanically based insecticides used on a large scale on stored commodities are pyrethrins, which are extracted from *Chrysanthemum* flowers. In the food processing industry, the major use of natural pyrethrins, in combination with the synergist piperonyl butoxide, is as a fog to control mainly flying insects, primarily by knocking them down. For commodity use, knockdown and repellency are both important, but in food processing facilities there are strict guidelines for when and where pyrethrins may be deployed to control insects; this is to prevent insects from falling into the commodity during processing and packaging.

8.4.2 RESEARCH NEEDS

Published protocols for efficacy studies are highly variable and could benefit from the development of standardized techniques. Techniques should also be developed to isolate and identify active compounds. Efficacy studies should consider how botanicals fit into an integrated pest management program. For example, compounds from higher plants may be antimicrobial, but also highly toxic to parasitoids and predators. Volatile molecules from plants may interfere with pheromone activity at the behavioral or receptor level. Botanical insecticides may interact either positively or negatively with inert dusts and controlled atmospheres. Insect sensitivity may be enhanced by applying a botanical with another material of a sublethal botanical preparation.

Studies on phyto-extracts may well lead to the development of modern methods of pest control based on semichemicals, which are at least as effective as the optimized synthetics but without conferring their disadvantages to either the consumer or the environment. These studies will contribute to our understanding on how in nature plants protect themselves against predators, and their mode of action. This is essential to enable us to learn how best to apply the phyto-extracts and facilitate their breakdown so as to prevent accumulation of residues in food. Information about the various agents that disrupt the insect life cycle (i.e., antifeedants, behavioral modifiers, toxicants, growth inhibitors, mating disrupters, oviposition inhibitors) could be used in the development of novel insect control approaches. For example, one line of approach might be to develop formulations that would repel insects from the cracks, crevices, and machinery in the food factories, followed by attraction and control elsewhere.

8.5 BIOLOGICAL CONTROL

8.5.1 PATHOGENS

Considering that the storage ecosystem is relatively easy to manage compared to field conditions, the potential for the manipulation of pathogens or of pathogen-based products could provide a promising insect control solution.

Cox and Wilkin (1996) listed advantages and disadvantages of biological control in stored products. Waage (1997) has outlined the dangers of viewing pathogens as mere biological analogues of chemical pesticides. Moore et al. (2000) reviewed the potential application of pathogens for the control of stored-product insects.

8.5.1.1 Bacteria

Bacillus thuringiensis (Bt) spores are associated with toxins that cause insect death mostly in *Lepidoptera*, but Bt strains that kill *Coleoptera*, *Diptera,* and other insects do exist (Krieg et al., 1983). The Bt product Dipel is registered in the United States for the application to grain to control moth pests. A general problem associated with Bt is the rapid development of resistance in moth pests, especially *P. interpunctella* (McGaughey, 1985). A proposed novel approach to the use of bacteria for insect control involves the application of *Pseudomonas syringae* to cause ice formation in insects at higher than normal temperatures. Other organisms also possess ice-nucleating activity. The fungus *Fusarium avenaceum* was shown to raise the supercooling point of the rusty grain beetle, *Cryptolestes ferrugineus,* from –17° to –9°C and *P. syringae* from –17° to –6°C. This approach creates possibilities of controlling *C. ferrungineus* at higher temperatures than those that would at present achieve control at low temperatures (Fields et al., 1995).

8.5.1.2 Fungi

There are many species of entomopathogenic fungi recorded, but most of the limited work related to stored-product pests has been done with *Beauveria bassiana* and

Metarhizium anisopliae. Searle and Doberski (1984) investigated *B. bassiana* against *O. surinamensis* and found humidity to be the critical factor. Dales (1994) concludes that fungi are unlikely to be generally useful for the control of storage pests, because the dry conditions that prevail in storage situations are unsuitable for fungal activity. Stathers (2002) reported on an oil-based formulation of *B. bassiana* applied to maize cobs. Although within 4 months after treatment, the *Prostephanus truncatus* densities were unacceptably high, they were significantly lower in the treatments to which conidia had been applied than in the controls.

8.5.1.3 Baculoviruses

Baculoviruses are pathogenic to invertebrates, especially *Lepidoptera* (Tinsley, 1979; Granados and Federici, 1986). Baculoviruses have rarely been reported from *Coleoptera* and not at all from stored-product beetles. They are the most common group of insect viruses and are usually host-specific or nearly so (Huber, 1990). Most baculoviruses, both nuclear polyhedrosis virus (NPV) and granulosis virus (GV), produce crystalline occlusion bodies and are consequently protected until ingested by insects.

Most, if not all, baculoviruses can be transmitted from an infected female to her progeny via the egg. This mode of transmission offers the potential to contribute to the success of the autodissemination approach to application (Vail et al., 1993).

An economic assessment suggested that costs would be comparable with fumigation and modified atmospheres (Vail and Tebbets, 1991).

8.5.1.4 Protozoa

Protozoa are single-celled organisms that usually enter the host by ingestion or passage from mother to progeny. The *Gregarinida* and *Coccidia* are parasites of the fat body, Malpighian tubes, or gut of insects and are characterized by resistant, spore-like, or encysted stages (Cox and Wilkin, 1996).

A neogregarine of great potential is *Mattesia trogodermae*. A cosmopolitan pathogen of *T. granarium,* it is also capable of suppressing *T. glabrum* populations under simulated warehouse conditions using pheromone lures for spore dissemination (Shapas et al., 1977; Brooks, 1988).

Mattesia dispora has been recorded from several *Coleopteran* and *Lepidopteran* species, including *Galleria mellonella* (Duhlinska, 1986), *C. ferrugineus* (Finlayson, 1950), *E. kuehniella* (Naville, 1930), and *P. interpunctella* (Weiser, 1954), among others. The microsporidia, *Nosema* species, have also been isolated from *Prostephanus truncatus* (Schulz and Laborius, 1987), but most work with the group relates to *Nosema whitei* in *Tribolium* species (Dales, 1994). Many other pathogenic protozoa remain to be isolated from stored-product insects, and their impact on pest populations will deserve serious consideration.

8.5.1.5 Nematodes

There appears to be no work published on the use of nematodes against pests in storage (Cox and Wilkin, 1996). The accepted view is that nematode application to stored grain is extremely unlikely, as they usually require a wet environment (Cox and Wilkin, 1996).

8.5.2 PARASITOIDS AND PREDATORS

The storage environment is favorable for the reproduction of natural enemies as long as the insects and mites that host them are available. The use of insect parasitoids and predators to control stored-product insect pests was reviewed by Arbogast (1984a; 1984b), Brower (1990, 1991), Nilakhe and Parker (1990), Burkholder and Faustini (1991), Brower et al. (1996), Scholler et al. (1997), Adler and Scholler (1998), and Scholler and Flinn (2000).

Scholler (1998) listed 58 species of parasitoids and predators of 79 stored-product pests. These parasitoids and predators were categorized by Scholler and Flinn (2000) into generalists and specialists. Generalists prey on a variety of unrelated species. Specialists tend to forage for a few closely related host species. Since stored commodities can be very often infested by more than one species, releasing a combination of a generalist and specialist parasitoids or predators is preferable (Press et al., 1982; Brower and Press, 1992).

Predators are generally specialized on certain developmental stages of prey species belonging to a certain insect order. Several stored-product predators belong to the order Hemiptera. For example, *Xylocoris flavipes* (Jay et al., 1968), *Lyctocoris campestris* (Parajulee and Phillips, 1994), and *Calliodes* species (Boye, 1988), are predatory hemipterans that specialize on eggs and early instars of insects, whereas *Teretriosoma nigrescens* is a histerid beetle that preys on immature stages of beetles and is closely associated with *P. truncatus* (Rees, 1985; Poschko, 1993). Predators kill their prey immediately and require several prey individuals to complete their development**.** As opposed to parasites, which develop inside a single host, the predators move from host to host, frequently being bigger than the host itself.

8.5.2.1 Use of *Teretriosoma nigrescens* in Africa

The bostrichid *P. truncatus* is a well-established corn pest in South America. At the end of the 1970s it spread to Tanzania, where in the absence of natural enemies it spread to neighboring countries and through West Africa to become a severe stored-product pest, attacking mainly corn and cassava chips. Both the adults and larvae of *T. nigrescens* prey on eggs and larvae of *P. truncatus*. Rees (1985) found that about 60 larvae of *P. truncatus* were consumed by *T. nigrescens* to complete larval development. However, because of their relatively long developmental time and small number of progeny, mass-rearing of *T. nigrescens* was not thought to be cost-effective (Markham et al., 1994).

T. nigrescens can maintain itself on plant substrates, but reproduction does not take place without the host (Poschko, 1993). After its first release in Togo in 1991, it was then released in Kenya, Benin, Ghana, and Guinea. In view of its positive properties as a natural enemy of *P. truncatus*, its release was recommended to other countries in Africa where *P. truncatus* occurs.

8.5.2.2 Research Needs

Field studies on the applicative aspects of rearing, quality control of the natural enemies, transport, and their release methods are needed. Programs must address the development of an infrastructure to supply beneficial insects. Models predicting the number of natural enemies to be released and the timing of releases are needed for additional species of natural enemies. Additional estimates of the cost of biological control are needed for a variety of storage and processing facilities. Above all, field tests to demonstrate the effectiveness of natural enemies in a variety of storage and processing facilities, and their compatibility with other pest management methods, are needed.

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