20

Dried Fruits and Tree Nuts

Judy A. Johnson, Elhadi M. Yahia, and David G. Brandl

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20.1 Introduction

Dried fruits and tree nuts are relatively high-value products used primarily for snack foods or as confectionary ingredients, and their successful marketing requires strict attention to quality control. The United States alone produces nearly 1.5 million metric tons each year of almonds, hazelnuts, macadamias, pecans, pistachios, walnuts, dates, figs, prunes, raisins, and dried apricots, worth more than $3 billion (USDA, 2007). These are also valuable products for the foreign export market, important to the economies of such major producers as the United States and Turkey.

Dried fruit and tree nuts typically have one or more preharvest insect pests that feed directly on the product and are capable of causing considerable damage and quality loss (Simmons and Nelson, 1975). Although many of these may be present at the time of
harvest and are often brought into storage, they generally do not reproduce under storage conditions (Johnson et al., 2002). However, because they may continue to feed and cause additional damage, and often present phytosanitary problems for processors, they are considered postharvest pests. Feeding damage by these insects also may provide entry to aflatoxin-producing molds (Aspergillus spp.) (Campbell et al., 2003). Initial disinfestation of an incoming product is sufficient to control these pests and reduce their damage. These commodities are also susceptible to attack by a number of common stored product moths and beetles, the most serious being the Indianmeal moth, Plodia interpunctella (Simmons and Nelson, 1975). Because stored product pests are capable of repeated infestation during storage, long-term protective treatments or repeated disinfestation treatments are necessary for their control.

Current insect control measures for dried fruit and nuts depend largely on fumigation to disinfect large volumes of incoming product during harvest, as well as to control storage infestation (Johnson, 2004). Methyl bromide, a fumigant used in a wide range of postharvest applications, is scheduled for worldwide withdrawal from routine use as a fumigant in 2015 under the Montreal Protocol on ozone-depleting substances (UNEP, 2006), and its use has already been severely restricted in developed countries. Resistance to phosphine, often used as an alternative to methyl bromide for dried fruit and nut crops in developed countries, has been documented in many insect populations (Benhalima et al., 2004), and some regulatory agencies have expressed concerns over worker safety with this compound (Bell, 2000). Sulfuryl fluoride, long used for structural fumigation, has recently been registered for commodity fumigation in several countries including the United States (Prabhakaran and Williams, 2007), but reduced toxicity of this compound against insect eggs and at lower temperatures (Bell and Savvidou, 1999) may limit its applicability. Moreover, there is a mounting pressure against the general use of chemical fumigants due to atmospheric emissions, safety, or health concerns, and an increased interest in organic food production, resulting in efforts to develop nonchemical technologies as alternative control methods for insects. Among these technologies are low and high temperatures, irradiation, and modified atmosphere (MA) and controlled atmosphere (CA).

Dried fruits and nuts, like most low-moisture, durable commodities, often tolerate extreme MA and CA (very high CO$_2$ and/or very low O$_2$) at levels used to control insects. More than 25 years ago, the U.S. Environmental Protection Agency approved carbon dioxide, nitrogen, and combustion product gases as a means to manage insects infesting raw and processed agricultural products, including dried fruits and tree nuts (Johnson, 1980, 1981). While current insect control measures for dried fruits and nuts still rely on fumigation, there is some limited commercial use of MA and CA for these products, primarily for organic product lines. This chapter will discuss the potential applications and effect on product quality of MA and CA treatments for insect control in dried fruits and tree nuts.

### 20.2 Applications for Insect Control

A variety of insects, infesting the product either in the field or during storage, may be found in postharvest dried fruits and nuts (Table 20.1). Although infestations cause direct damage through feeding and by contaminating product with excreta, webbing, and exuvia, these loses are relatively low. Increased losses occur when infestations cause the implementation of regulatory actions or, worse yet, loss of consumer confidence. The presence of any live insects may impact trade, particularly to foreign markets. Some states and countries consider certain field pests, such as codling moth, filbertworm, and

<table>
<thead>
<tr>
<th>Postharvest Storage Pests - Almond moth</th>
<th>Indianmeal moth</th>
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</thead>
<tbody>
<tr>
<td>Grain and flour beetles</td>
<td>Various beetles</td>
</tr>
<tr>
<td>Vinegar flies</td>
<td>Curculio Spp., to be quilted of product to prevent products are cosmopolitan subject to quarantine inspectors.</td>
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Correctly applied, rates for field pests but prevent further damage to stored products are cosmopolitan subject to quarantine inspectors.

Disinfestation treatments, processing and storage residues on marketed products, mental and workers’ health, fruit and nut products, no single disinfestation, wide range of applicability, any alternative treatment is too costly. For some controlled atmospheres.

The volumes of dried fruits and time to meet the de
Curculio spp., to be quarantine pests, and as such require specific disinfection treatments of product to prevent pest introductions. While most of the storage insects found in these products are cosmopolitan in distribution (Simmons and Nelson, 1975), and are not usually subject to quarantine restrictions, they can cause the rejection of product when found by inspectors.

Correctly applied preharvest pest management practices result in very low infestation rates for field pests, but disinfection treatments shortly after harvest are often necessary to prevent further damage and meet phytosanitary standards. Because most field pests rarely reproduce in storage, a single treatment is sufficient. In contrast, populations of common stored product insects such as the Indianmeal moth may increase rapidly under storage conditions. Dried fruits and tree nuts are considered durable products, and may be held in storage for months or even years, during which the product is always at risk of reinfestation by storage pests. Strategies emphasizing exclusion, sanitation, and use of protective treatments are effective in controlling storage pests, but dried fruit and nut processors commonly rely on one or more disinfection treatments to ensure insect-free products.

Disinfection treatments must be efficacious, economical, applicable to the existing processing and storage system, and must not harm product quality or leave chemical residues on marketed product. Also, for treatments to be completely accepted, environmental and worker safety concerns should be manageable. Because of the diversity of dried fruit and nut products, their production, storage, and marketing methods, and volumes handled, no single disinfection method is suitable for all situations (Johnson, 2004). Fumigants are commonly used because of their efficacy, economy, and suitability to a wide range of applications (Hagstrum and Subramanyam, 2006). To be widely adopted, any alternative treatment must be as effective and practical as fumigants, and must not be too costly. For some applications within the dried fruit and nut industry, modified and controlled atmospheres may be useful.

The volumes of dried fruits and nuts that must be treated within relatively short periods of time to meet the demands of various markets are sometimes quite large when compared...
to fresh horticultural commodities. MA and CA treatments are successful in replacing chemical fumigants only when they can be applied in a practical, timely, and economical manner to these large volumes. Consequently, research has concentrated on the application of MA or CA to existing processing methods and storage systems (Figures 20.1 and 20.2), in order to avoid drastic changes to facilities and to keep costs low. The methods used to generate treatment atmospheres include gas from cylinders (Figure 20.3), exothermically generated low oxygen atmospheres (GLOA) using combustion to reduce oxygen levels (Storey, 1975), and gas separation systems (Johnson et al., 1998, 2002; Figure 20.4). Another form of modified atmosphere treatment is the use of low pressures to obtain reduced oxygen tensions (Navarro et al., 2003; Figure 20.5).

FIGURE 20.1
Some examples of dried fruit and nut storage found in the central valley of California. Clockwise from top: walnut silos, Fibreen covered raisin stacks; and plastic covered almond piles.

FIGURE 20.2
Common method of sun drying raisins on paper trays.

FIGURE 20.3
Almond silos being treated with low oxygen atmospheres (GLOA).

FIGURE 20.4
Hollow fiber membrane gas separation system for modified atmosphere treatment.

20.2.1 Dried Fruits and Nuts

Sun-dried fruits store in a variety of insects and vinegar flies, nitidulid beetles, and of excessive moisture, almond moth, almond powder post moth, and almond flour moth (Tribolium castaneum), also be found (Smith, 1990).
Dried Fruits and Tree Nuts

20.2.1 Dried Fruits

Sun-dried fruits such as raisins or figs are susceptible to attack as the product dries by a variety of insects such as raisin moth (Cadra figulilella), nitidulid beetles (Carpophilus spp.), and vinegar flies (Drosophila spp.) (Simmons and Nelson, 1975). Some, in particular, nitidulid beetles and vinegar flies, may continue to reproduce in storage under conditions of excessive moisture. The most common pests infesting product in storage are Indian meal moth, almond moth (Cadra cautella), grain beetles (Oryzaephilus spp.), and red flour beetle (Tribolium castaneum), although a variety of additional common stored product insects may also be found (Simmons and Nelson, 1975).
Soderstrom and Brandl (1984a) treated raisins using GLOA, with a combustion atmosphere of 0.5 kPa O₂, 12-14 kPa CO₂, 1.0 kPa argon, and the balance nitrogen. Stacks of raisin bins were treated under either polyethylene sheeting or Fibreen, a weatherproof paper laminated with tar and reinforced with fiberglass. The latter is commonly used for commercial raisin storage, and was secured to a wooden framework built around stacked raisin bins and sealed to the ground with oiled dirt. Using a continuous purge rate of 12.7 m³/h, oxygen levels in small raisin stacks (34 m³) covered with polyethylene dropped to 0.5 kPa in about 15 h. When adult *Oryzaephilus mercator*, adult red flour beetle and Indianmeal moth pupae were treated in these stacks, complete mortality was reached at 48, 72, and 96 h after purging began, respectively. Larger-scale tests used two Fibreen-covered raisin stacks, 1869 and 3308 m³, treated at an initial purge rate of 283 m³/h to reduce oxygen to the target level of <0.5 kPa (Table 20.2). Of the insects treated, *Drosophila melanogaster* pupae and more than 200 raisins may be storable for extended periods, and mortality times are not unusual.

A study by Soderstrom and Brandl (1984a) investigated the efficacy of GLOA treatments in two different sizes of Fibreen-covered raisin stacks. Table 20.2 presents the parameters and results of these treatments.

### Table 20.2: Efficacy of GLOA Treatments in Two Different Sizes of Fibreen-Covered Raisin Stacks

<table>
<thead>
<tr>
<th>Parameters</th>
<th>3308 m³ Stack</th>
<th>1869 m³ Stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial purge rate</td>
<td>283 m³/h</td>
<td>283 m³/h</td>
</tr>
<tr>
<td>Time to 0.5 kPa O₂</td>
<td>48 h</td>
<td>24 h</td>
</tr>
<tr>
<td>Maintenance purge rate</td>
<td>17 m³/h</td>
<td>14-17 m³/h</td>
</tr>
<tr>
<td>Average temperature</td>
<td>27°C</td>
<td>WC</td>
</tr>
</tbody>
</table>

Exposure needed for 100% mortality (time is from the beginning of initial purge):

- *Cadra figulilella* pupae: 72 h
- *Plodia interpunctella* pupae: 48 h
- *Drasaphilina melanagaster* pupae: 120 h
- *Carpophilus hemipterus* mixed cultures: 60 h
- *Oryzaephilus surinamensis* adults: 48 h
- *O. surinamensis* larvae: 48 h
- *Tribalia castaneum* adults: 48 h
- *T. castaneum* larvae: 60 h

melanogaster pupae proved to be the most tolerant, requiring 5 days (120h) at around 27°C, and more than 2 weeks at around 16°C. Although these treatment times may seem lengthy, raisins may be stored in Fibreen-covered stacks for several months, and such treatments times are not unacceptable. Phosphine is the fumigant of choice for such stacks and treatment requires a minimum of 3 days at 27°C (Soderstrom et al., 1984).

An economic analysis was made of CA treatment of raisins, comparing costs for methyl bromide, phosphine, GLOA, and nitrogen (Gardner et al., 1982). At the time of the analysis, the GLOA system was found to be competitive with both methyl bromide and phosphine, and further cost savings were seen when heat from the generators was recovered for use in plant heating systems. Use of liquefied nitrogen was found to be the most costly. A more refined analysis (Soderstrom et al., 1984) found the cost of GLOA ($9.66-$10.64/jMT) to be slightly lower than phosphine ($10.76/jMT). At the time of this analysis, methyl bromide was the least costly ($8.39/jMT). Since these studies were done, the cost of methyl bromide has increased considerably, largely due to restrictions imposed by the Montreal Protocol. Methyl bromide prices in the west coast of the United States increased by about 400% from 1995 to 2001 (UNEP/TEAP, 2001), and may have made CA more competitive with the fumigant.

While early GLOA systems were shown to be efficacious and cost effective, concerns about safety, rising natural gas prices, environmental issues, and the continued availability of relatively inexpensive fumigants prevented adoption of the method by processors. As the demand for organic raisins increased, some processors revisited CA treatments as an alternative, and began using liquid nitrogen to disinfest raisins stored in Fibreen-covered yard stacks.

Researchers in the Middle East have used a variety of methods to generate modified atmospheres to treat durable commodities such as dried fruits, including liquid CO2, hermetic storage, and vacuum treatments. Treatments were often applied within flexible, plastic containers developed for low cost, portable grain storage, known as Volcani Cubes or GrainPro Cocoons (Donahaye et al., 1991). Navarro et al., (1998a) used such a container system to apply CA treatments to disinfest dates of nitidulid beetles. An atmosphere of 60-85 kPa CO2 and 4-7 kPa O2 generated from cylinderized liquid CO2 was applied within a 151 m³ chamber partially filled with 30 t of dates stacked in crates on pallets at temperatures of 22°C-28°C. During the initial purge, a CO2 concentration of about 85 kPa CO2 was obtained in the chamber within 1 h by introducing the gas under high pressure, and was maintained for 10 days. After that, CO2 levels were maintained at about 60 kPa CO2 for 4.5 months using approximately 0.8 kg CO2/day. Insect populations were effectively controlled using this regimen, and no significant difference in quality was found between the treated dates and controls stored at -18°C.

Related laboratory studies showed that CO2 levels >20 kPa, low O2 levels <7 kPa, and low pressures <170 mmHg caused Carpophilus hemipterus to leave artificial refuges at a rate comparable to methyl bromide treatments (Navarro et al., 1989). The low pressure treatments, which provided O2 levels of <4.7 kPa, were the most effective means of disinfestation, with more than 80% of the beetles leaving refuges after just 10 min of exposure. However, exposure periods for these treatments in excess of 24 h would be needed to cause complete mortality (Navarro et al., 1998b).

Another study used storage under low pressure to control insect infestation in stored dates (Hussain, 1974). When infested dates are packed in polyethylene bags at pressures of 10-20 kPa, insect mortality was 100% after 2 days.

The effect of GLOA on Cadra cautella infestation in dried figs was studied by Damarli et al. (1998). An exothermic generator that maintained 1 kPa O2 and 10-15 kPa CO2 in a 6 m³ shipping container was used at 25°C-35°C for 24-72 h. Dried fig samples of 3-4 kg to 8.5 t were infested with C. cautella larvae (16-22 days old) and eggs (24, 48, and 72 h old).
effects of repeated cycles of 0.4-1.4 h and the higher concentrations 0.3 mg·mL⁻¹ for 24 h. DDVP alone caused 100% mortality after 24 h of treatment at 22°C. In a related field study, Brandl et al. (2004) applied cylinderized CO₂ treatments for 20 h at 22°C and 36°C, with CO₂ levels of 9.5 kPa and 20 kPa, respectively, and found that CO₂ alone caused 100% mortality of the eggs, larvae, and adults of the navel orangeworm. A combined treatment of CO₂ and DDVP for 24 h at 22°C resulted in 100% mortality of the eggs, larvae, pupae, and adults of the navel orangeworm. These results suggest that temperatures above 38°C could be useful in reducing treatment times for CA, but warn that prior exposure to elevated temperatures should be avoided. Donahaye et al. (1994) also showed the effect of increasing CO₂ concentrations (60-98 kPa) or decreasing O₂ concentrations (0.5-5 kPa) caused progressively greater mortality of red flour beetle larvae (Soderstrom et al., 1992). Mortality was also increased by increasing temperature (38°C-42°C). However, pretreatment conditioning at 38°C for 24 or 48 h significantly reduced mortalities for the highest CO₂ and lowest O₂ treatments. These results suggest that temperatures above 38°C could be useful in reducing treatment times for CA, but warn that prior exposure to elevated temperatures should be avoided. Donahaye et al. (1994) also showed the effect of increasing temperature on efficacy of low O₂ treatments for nitidulid beetles (Carphophilus hemipterus and Urophorus humeralis). For both species LT₅₀ values for 1 kPa and 2 kPa O₂ at 35°C were usually less than half those at 26°C.

Tarr and Clingeleffer (2005) treated eggs, pupae, and adults of the red flour beetle in hermetically heat-sealed gas barrier bags containing 500 g of golden-colored, sultana raisins, with or without the addition of a commercial O₂ absorber. The bags were held at 30°C for 9 days, 22°C for 20 days, or 15°C for 45 days. These times exceeded the minimum time recommended by Annis (1987) for population extinction of red flour beetle under low O₂ conditions. O₂ levels in the bags with or without the O₂ absorber were ~1.7 kPa, and 2.9-16.3 kPa, respectively. All fruit samples treated with O₂ absorbers produced 100% mortality, with no occurrence of a second-generation population, when incubated post-treatment at 27°C for 60 days. Fruit stored in hermetically sealed bags without O₂ absorbers at 22°C and 30°C produced 100% adult mortality but eggs and pupae survived. Results at 15°C were confounded by complete control mortality of eggs and pupae, suggesting that the low temperature alone had a great effect. The low O₂ atmosphere was also found to minimize raisin color change during storage.

The psocid Liposcelis bostrychophila is a common insect pest, which infests a variety of processed and unprocessed stored foods in households, granaries, and warehouses. Psocids are highly resistant to most forms of pest control, and their populations in stored foods have increased alarmingly in some regions of Asia. Ding et al. (2002) examined the

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effects of repeated exposures to low O\textsubscript{2} CA (1 kPa O\textsubscript{2}, 35 kPa CO\textsubscript{2}, and 64 kPa N\textsubscript{2} for 4-14 h) and the insecticide dichlorvos (dimethyl dichloro-vinyl phosphate, DDVP 80%, 0.3 mg/mL for 24 h) on population growth and development of resistance of \textit{L. bostrychophera}. Psocid populations were treated and evaluated every 2 weeks over an 11 week period with CA, with DDVP, or with alternating treatments of CA and DDVP. An untreated population increased 48.1-fold over the 11 week period. Neither CA nor DDVP alone controlled psocid population growth. However, alternating CA and DDVP treatments resulted in a significant increase in mortality compared with either treatment alone. After six exposures, resistance in populations exposed to either CA or DDVP alone increased 1.8- and 2-fold, respectively, and probit analysis of data suggested that further increased resistance was possible. Results of this study have indicated that alternating CA with insecticide applications could be a more effective management measure for control of psocids in stored foods than use of these treatments alone.

20.2.2 Tree Nuts

As with dried fruits, tree nuts may be infested with field pests during harvest. For nut crops such as almonds, that are most often sun dried, or walnuts, which are dehydrated at relatively low temperatures, these field pests are capable of continued damage in storage, and may be a phytosanitary concern in exported product (Johnson, 2004). In addition, nearly all tree nuts are susceptible to infestation by common stored product insects such as Indianmeal moth, grain beetles, and red flour beetles.

In California, the navel orangeworm, \textit{Amyelois transitella}, is a serious pest of the three major tree nut crops: almonds, pistachios, and walnuts. Although primarily a field pest, navel orangeworm may be brought into storage where younger larvae may continue to damage by moving to uninfested nuts (Curtis et al., 1984; Soderstrom and Brandl, 1984b). Storey and Soderstrom (1977) began investigations on the use of CA to control navel orangeworm using an exothermically generated low O\textsubscript{2} atmosphere (1 kPa O\textsubscript{2}, 9-9.5 kPa CO\textsubscript{2}, with the balance mostly N\textsubscript{2}). Pupae and mature larvae were found to be the most tolerant to low oxygen treatments, with \textsc{LT}_{95}s of 145 and 138 h at 18°C, respectively, and 38 and 37 h at 27°C, respectively. Sublethal exposures of low oxygen to adult navel orangeworm were found to reduce their progeny number; no progeny were produced after adults were exposed for 8 h, while 24 h exposures were required for complete adult mortality.

Brandl et al. (1983) examined the effect of various levels of O\textsubscript{2} and CO\textsubscript{2} on navel orangeworm mortality and determined that low O\textsubscript{2} was more important in reducing treatment times than CO\textsubscript{2}. Further study (Soderstrom et al., 1986) looked at the interaction of O\textsubscript{2} concentration, temperature, and relative humidity (RH) on the time needed to control navel orangeworm and Indianmeal moth. The two test species differed in their response; Indianmeal moth was more affected by changes in O\textsubscript{2} concentrations while navel orangeworm responded more strongly to changes in RH. It was suggested that navel orangeworm, as a pest that feeds mainly on product with a higher moisture content, is less tolerant to changes in relative humidities. Indianmeal moth, found in drier storage environments, is better able to survive low relative humidities.

The effect of low O\textsubscript{2} or elevated CO\textsubscript{2} atmospheres on insect feeding was examined by Sodertrom and Brandl (1982). Feeding of navel orangeworm and Indianmeal moth larvae treated for 20 h with various levels of O\textsubscript{2} and CO\textsubscript{2} was determined through a red dye contained in the rearing medium. Both the lowest level of O\textsubscript{2} (1 kPa) and highest level of CO\textsubscript{2} (40 kPa) significantly reduced larval feeding of both species. Navel orangeworm was more susceptible, particularly to high CO\textsubscript{2}. Therefore, these results indicate that purging the storage at the beginning of nut filling operation would be beneficial in reducing insect
damage to the nuts. CO₂ treatments were considered more practical because it was thought that 40 kPa CO₂ would be easier and cheaper to obtain in a rapid purge of treatment containers.

Soderstrom and Brandl (1984b) conducted a series of successful tests using GLOA to treat bulk stored almonds under plastic covers, in a 3000 ft steel silo, and in 30 m by 7.3 m diameter concrete silos containing 450 MT of inshell almonds. The initial purging of the concrete silo took 8 h, and 100% mortality of Indianmeal moth and navel orangeworm pupae was reached at 36 and 60 h after purging, respectively.

Codling moth (Cydia pomonella L.) is a common field pest of California walnuts. Although it does not reproduce in storage, it is considered a quarantine pest by some countries, and processors have relied on methyl bromide to disinfest incoming product (Johnson, 2004). Diapausing codling moth larvae may be in harvested walnuts, and were found to be the most tolerant life stage to both low O₂ and high CO₂ atmospheres at 25°C, with the lowest LT95 (13.6 d) obtained at 60 kPa CO₂ and 60% relative humidity (Soderstrom et al., 1990). Such extended treatment times are not acceptable to processors, who must quickly disinfest incoming product to meet market demands. To reduce treatment times, high-temperature CA treatments were investigated as a methyl bromide alternative for codling moth in shell walnuts (Soderstrom et al., 1996a). Temperatures (39°C, 41°C, 43°C, and 45°C) selected were those suitable for walnut dehydration without adversely affecting quality. Treatment atmospheres were 98 kPa CO₂ in air, 0.5 kPa O₂ in N₂, and a simulated combustion atmosphere of 0.5 kPa O₂, 10 kPa CO₂, and the balance N₂. Elevated temperatures dramatically reduced treatment times for all atmospheres, including normal air. The most effective treatment tested was 98 kPa CO₂ and 60% RH, with estimated probit 9 values of 3.6 and 6.6 h for 45°C and 43°C, respectively.

Based on the results found in Soderstrom et al. (1996a), a prototype treatment chamber for rapid application of high temperature alone or with CA was designed and tested for disinfesting walnuts of diapausing codling moth larvae (Soderstrom et al., 1996b). The chamber was made of fiberglass insulated polyvinyl chloride pipe, and was designed to allow quick heating and controlled atmosphere recirculation under air tight conditions. The chamber held a mass of about 30 kg of inshell walnuts that was 1.2 m deep and 0.3 m in diameter. Air flow during the initial heating phase was 5.7 m³/min, which was reduced to 1.4 m³/min during temperature maintenance. Target temperatures were reached in about 1 h. Treatments evaluated were normal air, 0.5 kPa O₂ (in nitrogen), or 98 kPa CO₂ (balance air) at 43°C, and treatment exposures were based on estimated LT95 levels derived from Soderstrom et al. (1996a) (45.2 h for air, 14.6 h for 0.5 kPa O₂, and 5.2 h for 98 kPa CO₂). All treatments exceeded 95% mortality, and any surviving larvae were moribund and subsequently died.

An early economic analysis of the use of ionizing radiation as an alternative to chemical fumigants for dried fruit and nut disinfection used scenarios that included GLOA treatments (Rhodes and Baritelle, 1986). Although considerably more expensive than fumigants, GLOA treatments had a clear advantage over irradiation for almonds, walnuts, raisins, and prunes during long-term storage. A more current economic analysis was carried out for commercially available methyl bromide alternative treatments for disinfestation of almonds and walnuts, including phosphine fumigation, ionizing irradiation, and CA storage (Aegerter and Folwell, 2001). Costs for each alternative were estimated and compared to benchmark methyl bromide fumigation costs. Irradiation costs ranged from 2x to 14x the benchmark, while CA storage ranged from 1.7x to 2.5x the benchmark costs. PH₃ was used only to treat almonds, and its costs were only slightly higher than the benchmark. In all scenarios, CA was less expensive than irradiation. It was concluded that while these alternative treatments could effectively control insect populations in walnuts and almonds at a level comparable to methyl bromide, further research is needed to obtain approval for their use as quarantine treatments.

Navarro et al. (2004) concluded that while treatment times for CA and ionizing irradiation include control in durable plastic containers at 25°C, these treatments also cause adverse effects to the nuts. CO₂ atmospheres to disinfest walnuts were obtained from a preparation containing 450 MT of inshell walnuts, and processors have relied on methyl bromide to disinfest incoming product to meet market demands. To reduce treatment times, high-temperature CA treatments were investigated as a methyl bromide alternative for codling moth in shell walnuts (Soderstrom et al., 1996a). Temperatures (39°C, 41°C, 43°C, and 45°C) selected were those suitable for walnut dehydration without adversely affecting quality. Treatment atmospheres were 98 kPa CO₂ in air, 0.5 kPa O₂ in N₂, and a simulated combustion atmosphere of 0.5 kPa O₂, 10 kPa CO₂, and the balance N₂. Elevated temperatures dramatically reduced treatment times for all atmospheres, including normal air. The most effective treatment tested was 98 kPa CO₂ and 60% RH, with estimated probit 9 values of 3.6 and 6.6 h for 45°C and 43°C, respectively.

Based on the results found in Soderstrom et al. (1996a), a prototype treatment chamber for rapid application of high temperature alone or with CA was designed and tested for disinfesting walnuts of diapausing codling moth larvae (Soderstrom et al., 1996b). The chamber was made of fiberglass insulated polyvinyl chloride pipe, and was designed to allow quick heating and controlled atmosphere recirculation under air tight conditions. The chamber held a mass of about 30 kg of inshell walnuts that was 1.2 m deep and 0.3 m in diameter. Air flow during the initial heating phase was 5.7 m³/min, which was reduced to 1.4 m³/min during temperature maintenance. Target temperatures were reached in about 1 h. Treatments evaluated were normal air, 0.5 kPa O₂ (in nitrogen), or 98 kPa CO₂ (balance air) at 43°C, and treatment exposures were based on estimated LT95 levels derived from Soderstrom et al. (1996a) (45.2 h for air, 14.6 h for 0.5 kPa O₂, and 5.2 h for 98 kPa CO₂). All treatments exceeded 95% mortality, and any surviving larvae were moribund and subsequently died.

An early economic analysis of the use of ionizing radiation as an alternative to chemical fumigants for dried fruit and nut disinfection used scenarios that included GLOA treatments (Rhodes and Baritelle, 1986). Although considerably more expensive than fumigants, GLOA treatments had a clear advantage over irradiation for almonds, walnuts, raisins, and prunes during long-term storage. A more current economic analysis was carried out for commercially available methyl bromide alternative treatments for disinfestation of almonds and walnuts, including phosphine fumigation, ionizing irradiation, and CA storage (Aegerter and Folwell, 2001). Costs for each alternative were estimated and compared to benchmark methyl bromide fumigation costs. Irradiation costs ranged from 2x to 14x the benchmark, while CA storage ranged from 1.7x to 2.5x the benchmark costs. PH₃ was used only to treat almonds, and its costs were only slightly higher than the benchmark. In all scenarios, CA was less expensive than irradiation. It was concluded that while these alternative treatments could effectively control insect populations in walnuts and almonds at a level comparable to methyl bromide, further research is needed to obtain approval for...
their use as quarantine treatments. Again, rising fumigant prices since this analysis was done have improved the competitiveness of CA treatments relative to methyl bromide.

Navarro et al. (2003) showed the effectiveness of increased temperatures at reducing treatment times for both CO$_2$ and vacuum, and demonstrated the utility of flexible plastic treatment containers for the application of vacuum treatments for stored product insect control in durable commodities. Jo0Oson and Valero (2005) showed that relatively short exposures to low pressures of 6.66 kPa could control tree nut pests. Navel orangeworm eggs, diapausing Indianmeal moth, and diapausing codling moth larvae were found to be the most tolerant at temperatures of 25°C and 30°C. Field trials treating almonds in flexible plastic containers were done under both winter (nutmeats in wooden bins) and summer (in-shell almonds in 50 kg poly bags) conditions. Winter treatments at 6.3°C-10°C required extended treatment times of more than 13 days to get complete control. Summer treatments at 25°C-29°C provided complete control with a 48 h exposure.

Pecans are often infested with pecan weevil (Curculio caryae), which damages nutmeats and aids invasion of mold (Wells and Payne, 1983). Wells and Payne (1980) used high CO$_2$ atmospheres to disinfect pecans of this pest, and reduce the level of storage fungi. An atmosphere of 30 kPa CO$_2$ and 21 kPa O$_2$ in N$_2$ was effective at reducing fungal populations and completely killed weevils, but low O$_2$ atmospheres (1 kPa) with or without elevated CO$_2$ levels was noto.

Macadamia nuts produced on the island of Hawaii are often infested with the tropical nut borer, Hypothenemus obscursus (F.) (Delate et al., 1994). The beetle prefers to attack low moisture nuts on the ground or "sticktight" nuts remaining on the tree, and populations may continue to increase in nuts waiting processing. Postharvest control techniques, including CA treatments, were evaluated for control of this pest (Delate et al., 1994). Treatment chambers containing infested nuts and held at 24°C-30°C were flushed daily with either N$_2$ or CO$_2$ to maintain gas concentrations of 2:95 kPa. Tropical nut borer mortality was lower in nuts with the husk than without, possibly due to absorption of the gas by the husk. Unhusked nuts treated with 2:95 kPa CO$_2$ for 6 days resulted in 97.3% mortality of adult beetles, while all adult insects were killed at this exposure time and concentration when nuts were husked. Although CO$_2$ treatments provided slightly higher pest mortality, there were concerns over reduced nut quality after extended exposures. A 14 day treatment of 2:95 kPa N$_2$ was required for 100% mortality in unhusked nuts. Holding nuts under CA storage was suggested as a means of alleviating processing loads at the peak of the season without increasing damage due to the beetle.

20.2.3 **Combinations with Other Treatments**

Combining an initial, short-term CA disinfection treatment with long-term protective storage treatments in an integrated control program was shown to be promising as an alternative insect control strategy for walnuts (Jo0Oson et al., 1998) and for almonds and raisins (Jo0Oson et al., 2002). CA atmospheres were obtained with a hollow fiber membrane gas separation system in treatment rooms equipped with standard air expansion bags and sealed to a pressure half-life of 1 min after being pressurized to 0.245 kPa. For the initial CA disinfection treatment, 8 bins of product (3.6 MT of field-run raisins, or 1.8 MT of in-shell nuts) were treated at 0.4 kPa O$_2$ for 6 days at 25°C after a purge period of 2 days. Test insects for the initial disinfection treatment were navel orangeworm and raisin moth (Cadra figulilella), both common field pests of these products. After initial disinfection, four bins of product were moved to protected storage environments, either treatment with a preparation containing Indianmeal moth granulosis virus, low temperature (5-10°C) storage, or maintenance CA (5 kPa O$_2$). Mated female Indianmeal moths, the most serious storage pest of dried fruits and nuts, were added to the storage rooms each week.
TABLE 20.3
Survival of Target Insects after Disinfestation Treatment of 0.4 kPa O₂ for 6 Days at 25°C

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Number of Insects Treated</th>
<th>Adults Emerged</th>
<th>Survival (Yo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almonds (navel orangworm as test insect)⁹</td>
<td>Untreated control 403</td>
<td>393.0</td>
<td>97.5</td>
</tr>
<tr>
<td>CA</td>
<td>800</td>
<td>40.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Walnuts (navel orangworm as test insect)b</td>
<td>Untreated control 604</td>
<td>487.0</td>
<td>80.6</td>
</tr>
<tr>
<td>CA</td>
<td>1194</td>
<td>4.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Raisins (raiser moth as test insect)⁹</td>
<td>Untreated control 400</td>
<td>251.0</td>
<td>62.7</td>
</tr>
<tr>
<td>CA</td>
<td>800</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

⁹ Johnson et al. (2002).
b Johnson et al. (1998).

The initial disinfestation treatment was effective in controlling both test insects (Table 20.3), although there was some evidence that longer exposures might be necessary against raisin moth, or against diapausing navel orangeworm (Johnson et al., 2002). All protective treatments were effective in controlling Indianmeal moth (Table 20.4) and overall product quality was unaffected by any storage treatment. Storage under CA was the most efficacious in preventing infestation by Indianmeal moth, but the sealed storage prevented ready access to the product and the low O₂ atmosphere conditions present worker safety considerations that do not exist for the other methods. Extensive sealing of facilities and equipment for generating CA would be required to provide the needed storage conditions, and would result in considerable expense to processors. However, use of new technologies such as flexible plastic storage containers may help to bring these costs down.

TABLE 20.4
Indianmeal Moth Incidence and Related Damage in Almonds, Walnuts, and Raisins after Extended Storage at 5 kPa O₂

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Live Indianmeal Moth</th>
<th>Indianmeal Moth Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minor</td>
<td>Serious</td>
</tr>
<tr>
<td>Almonds (samples taken after 16 weeks)⁹</td>
<td>Untreated control 482.5</td>
<td>4.4</td>
</tr>
<tr>
<td>eA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Walnuts (samples taken after 16 weeks)b</td>
<td>Untreated control 81.0</td>
<td>12.6</td>
</tr>
<tr>
<td>CA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Raisins (samples taken after 40 weeks)a</td>
<td>Untreated control 3.2</td>
<td>13.2</td>
</tr>
<tr>
<td>CA</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Appendectomy: Each week mated females (5 for almonds and walnuts, and 15 for raisins) were added to the stored product
a Johnson et al. (2002).
b Johnson et al. (1998).

20.3.1 Almonds ("Nonpareil")
Kader (1996) states that almonds require storage at low O₂ to prevent growth. The effects of dryness on fresh, shelled and inshell almonds were observed by Guadagni et al. (1998). The content of a-tocopherol was stable than almonds stored for 86-89 kPa N₂ and 18-20 kPa N₂ at 1 and 2°C. Apricots were observed better when stored at 10°C, where the content of a-tocopherol increased. In particular, the content of a-tocopherol increased with the increase of the temperature used.

20.3.2 Apricots ('Nonpareil')
The effects of dryness on fresh apricot tissue were also monitored during drying pretreatments. Apricot slices were dehydrated apricots at 10-14°C. After 10 h, the content of a-tocopherol was 500%. In particular, the content of a-tocopherol increased with the increase of the temperature used. The content of a-tocopherol was always higher than 1000% at 10°C.
20.3 Effects on Quality

Although most of the uses of controlled atmospheres on bulk-stored dried fruits and nuts are for short-term insect disinfestation, modified or controlled atmospheres are often suggested as means to improve shelf life in these products, particularly for tree nuts. Because tree nuts are high in polyunsaturated lipids they are susceptible to oxidative rancidity (Watkins, 2005). Storage under low O2 conditions may greatly slow the development of rancidity. As such, vacuum packaging or N2 flushed packaging is often suggested to improve the shelf life of tree nuts. Consequently, much of the research on the quality effects of controlled atmospheres on tree nuts deals with exposures much longer than those necessary for insect disinfestation treatments. Although dried fruit quality is less affected by rancidity, MAs including elevated CO2 may reduce fruit darkening and improve shelf life.

20.3.1 Almonds (Prunus dulcis)

Kader (1996) states that O2 is the most important atmospheric component in almond storage, and that high O2 concentrations result in an increase in rancidity and mold growth. The effect of insecticidal GLOA treatments (>1 kPa O2, 9-9.5 kPa CO2, 86-89 kPa N2, and 1 kPa Ar) on almond flavor quality was determined by exposing shelled and inshell 'Nonpareil' almonds continuously to the atmosphere for 1-12 months (Guadagni et al., 1978a). At normal atmospheres, inshell almonds were found to be more stable than almond meats at both 18°C and 27°C, but no differences were detected under low O2 atmospheres. Low O2 was as effective as low temperature (18°C) in maintaining stability during storage, and caused less off-flavor development than normal atmosphere for both meats and inshell almonds.

The storage behavior of four varieties of almond ('Marcona,' 'Planeta,' 'Desmayo,' and 'Nonpareil') was investigated at two temperatures (8°C and 36°C), two packaging atmospheres (air and N2) and two treatments (raw and roasted) for up to 9 months (Garcia-Pascual, 2003). N2 packaging resulted in O2 levels <0.25 kPa. No significant differences were observed between air and N2 packaging for moisture, fat content, peroxide value, u-tocopherol content, and level of aflatoxins. A significant relationship was found between the increase of the peroxide value and the decrease of a-tocopherol content. The aflatoxin contents were always lower than 0.5 µg/kg.

20.3.2 Apricots (Prunus armeniaca)

The effects of drying, dehydration, and storage under CA on cell wall components of fresh apricot tissues were studied by Femenia et al. (1998). The degree of browning was also monitored during storage by measuring color and S02 content of dehydrated apricots. Apricots were treated with Na2S205 and acetic acid solutions before dehydration. Dehydrated apricots were then stored at 25°C in air or in five different CA treatments (100 kPa N2, 20 kPa CO2 and 80 kPa N2, 40 kPa CO2 and 60 kPa N2, 60 kPa CO2 and 40 kPa N2, 100 kPa CO2). The yield of apricot cell wall material decreased substantially during drying pretreatments and also during dehydration, by 9.5% and 4.7%, respectively. In particular, acetic acid solubilized a large amount of pectic polysaccharides. Further degradation of pectic substances occurred during drying, probably due to the high temperature used. CA storage retarded browning in comparison to the sample stored under air. The content of S02 decreased markedly for the sample stored in air, whereas gradual losses were observed for CA-stored samples. In general, samples stored in CA containing
low e\textsubscript{0} levels (20 and 40 kPa) showed minor disruption of cell wall components and better initial characteristics of dehydrated apricots.

20.3.3 Chestnuts (Castanea sativa)

Anelli et al. (1982) reported that chestnuts stored in 2 kPa O\textsubscript{2} plus 20 kPa e\textsubscript{0} at one had an increased rate of sugar metabolism. These chestnuts have also been reported to have lower glutamine content as the CO\textsubscript{2} level increased from 5 to 20 kPa. A prestorage treatment of 80 kPa CO\textsubscript{2} for 10 days followed by 80-90 days of storage at O°C was the best method of reducing Sclerotinia rot in chestnuts (Bertolini and Tonini, 1983). Rouves and Prunet (2002) examined various storage techniques for chestnuts, including low-temperature CA (2 kPa O\textsubscript{2} plus 5 kPa CO\textsubscript{2} at -1°C or 1°C). For the varieties ‘Marigoule’ and ‘Bouche de Betizac’ water loss was prevented, mold reduced, and taste maintained. The varieties ‘Comballe’ and ‘Marron de Goujonac’ did not benefit from CA storage.

20.3.4 Dates (Phoenix dactylifera)

Rygg (1975) suggested inert gas or vacuum packing for storage of high-moisture dates. Mohsen et al. (2003) noted that vacuum packaging is a useful technique for reducing darkening of the date for long-term storage. Mutlak and Mann (1984) reported that browning can be inhibited at low oxygen potentials. CA (5, 10, or 20 kPa CO\textsubscript{2}) at one extended storage period and maintained quality of fully mature ‘Bahri’ date fruit (AI-Redhaiman, 2005). The quality of fruit stored under 20 kPa CO\textsubscript{2} was maintained for up to 26 weeks compared to 17 weeks for fruit held under 5 and 10 kPa CO\textsubscript{2} and only 7 weeks for fruit kept in normal air. A 20 kPa CO\textsubscript{2} maintained acceptable levels of fruit soluble solids, total sugar, total tannins, and caffeoylshikimic acid.

20.3.5 Figs (Ficus carica)

The effect of insecticidal GLOA treatments on the quality of dried figs was studied by Damarli et al. (1998). An exothermic generator that maintained 1 kPa O\textsubscript{2} and 10-15 kPa e\textsubscript{0} atmosphere composition at 35°C for 30 h was used to treat 8.6 MT of product. Under these conditions, considered to be optimal for controlling insect populations, there were no observed negative effects on fruit weight, moisture, color, total sugar content, or acidity. Similarly, the effect of e\textsubscript{0} proposed for insecticidal treatments on dried fig quality was examined by Meyvaci et al. (2003a). Exposure to 100 kPa CO\textsubscript{2} for 45 days caused color changes as measured on the Hunter color scale with a colorimeter. In the Hunter scale, L measures lightness and varies from 100 for perfect white to zero for black, a measures redness when positive, gray when zero, and greenness when negative, and b measures yellowness when positive, gray when zero, and blueness when negative. In CA-treated figs, mean L values decreased from 57.9 to 51.7, a values increased from 9.8 to 11.7, and b values decreased from 30.6 to 27.7. In studies to improve shelf life of dried figs, Meyvaci et al. (2003b), packaging in 100 kPa N\textsubscript{2}, 20 kPa e\textsubscript{0} in N\textsubscript{2}, or under vacuum was examined for up to 7.5 months of storage. Figs stored under N\textsubscript{2} were darker than figs stored in normal air, while e\textsubscript{0} storage reduced darkening slightly. Figs stored under N\textsubscript{2} also had increased sugar formation. Vacuum packaging resulted in the darkest fruit, but reduced sugar formation. Storage under either N\textsubscript{2} or CO\textsubscript{2} controlled mold growth in rehydrated figs for 3 months more than storage at ambient conditions.

20.3.6 Hazelnut

Hazelnut is characterized in unsaturated fats (Czajkowska, 2001). Storage conditions help preserve quality (Labavić et al., 2003). Nitrogen (~99.5% of natural) is usually used for 1 year or more (Eggeling et al., 1956). Storage of ‘Piemontese’ chestnuts at 3°C and 50% RH in nitrogen (~99.5%) prolonged the shelf life of the chestnuts compared to room temperature conditions (3°C-6°C, 50%-60%). CA conditions by storing hazelnuts at 3°C and 50% RH in CO\textsubscript{2} (7°C and 25°C) at 100% humidity caused significant increase in the peroxide values. CA conditions caused significant reduction in the fatty acid loss at the monolayer condition (Estevez et al., 2006).
20.3.6 Hazelnuts, Filberts (*Corylus* spp.)

Hazelnut is characterized by high oil content (about 65% of its kernel weight) and is rich in unsaturated fatty acids, and therefore highly sensitive to rancidity (San Martin et al., 2001). Storage conditions that are capable of retarding lipid oxidation and hydrolysis will help preserve quality. Reduced temperature may be effective in combination with other protective measures such as vacuum packaging in extending roasted kernel shelf life to 1 year or more (Ebraheim et al., 1994). Keme et al. (1983) reported that it is possible to store 'Piemonteses,' 'Roman,' and 'Akakocca' hazelnuts at ambient temperature under nitrogen (<2 atm) for prolonged periods of time with a loss of quality that is comparable to that resulting from storage conditions at low temperatures and controlled RH (3°C-6°C, 50%-60% RH). Hazelnut ('Negret') quality was studied after storage in selected CA conditions by San Martin et al. (2001). The shelled and unshelled hazelnuts were stored with different oxygen levels (1, 5, 10, and 20 kPa O₂) at two different temperatures (7°C and 25°C), and quality of the hazelnuts during storage was monitored by determining the peroxide value, acid value, K₂₃₂, and K₂₇₀ indices, percentage of unsaturated fatty acids and sensory analysis. After 1 year in storage, none of the storage conditions tested caused significant rancidity. Storage in atmospheres with O₂ levels lower than 10 kPa significantly reduced autoxidation and the low temperature delayed lipid rancidity.

20.3.7 Macadamia (*Macadamia integrifolia*)

As with other nuts, prolonged exposure to O₂ results in rancidity, and vacuum packaging or nitrogen flush offers protection from O₂ (Cavaletto, 2004).

20.3.8 Pecan (*Carya illinoinsis*)

Shelf life of pecans may be increased by storage in 2-3 kPa O₂ in N₂, and less frequently using CO₂ as the balance gas (Maness, 2004). Storage in <2 kPa O₂ for 52 days can cause the development of a "fruity" flavor (Santerre et al., 1990). O₂ transmission rates for packaging materials should be >0.08 mL/100 cm² per 24 h (Dull and Kays, 1988). Vacuum packaging can offer a further benefit of protection from breakage.

20.3.9 Pine Nuts (*Araucaria* spp.)

Pine nuts (piñones), *Araucaria araucana*, stored in different MA (polyethylene bags lined with volcanic dust) and CA (10-5 kPa CO₂-O₂, and 20-5 kPa CO₂O₂) conditions maintained their moisture and starch content, and 20-5 kPa CO₂O₂ was the optimum CA condition (Estevez and Galletti, 1997).

20.3.10 Pistachio (*Pistacia vera*)

Although pistachios are fairly stable stored in normal air at 20°C, storage under reduced O₂ (<0.5 kPa), vacuum packaging or N₂ flushed packaging further improves flavor stability (Labavitch, 2004a). Changes in fatty acid composition and peroxide value of pistachio nuts were studied during storage at 10°C-30°C under either air or 98 kPa CO₂ at the monolayer moisture content of pistachios (considered to be the most stable moisture content for storage of dehydrated products), and were compared to those stored under ambient conditions (Maskan and Karatas, 1998). Use of the Arrhenius model to predict fatty acid loss at 10°C, 20°C, and 30°C under both atmospheric conditions, together with prediction of the rate and extent of oxidation during storage, was also investigated. Storage
of pistachio nuts under CO₂ provided the greatest stability in relation to fatty acid loss, peroxide values, and free fatty acid formation, especially at 10°C. The Arrhenius model revealed that storage of nuts under CO₂ was more temperature sensitive, and more linolenic acid was lost by oxidation than linoleic acid. Comparison of samples stored at ambient conditions with those stored at or near the monolayer moisture content and under CO₂ storage showed the latter samples to be more stable.

Storage stability, oil characteristics, and chemical composition of whole-split pistachio nuts (Pistachia vera L.) were determined on samples stored in CA (2 kPa air, 98 kPa CO₂) at the monolayer value at 10°C, 20°C, 30°C, and at ambient conditions (Medeni and Sukru, 1999). Most oxidation was observed under ambient storage conditions. CO₂ especially improved the storage stability at low temperatures. Using the reaction rate constants of peroxide formation, it was revealed that as temperature increased, the ratio of rate constants (air/CO₂) approached 1, which means that no significant difference existed between air and CO₂ storages at 30°C. The oxidation activation energies were 8.33 and 13.39 kcal/mol under air and CO₂ storage, respectively.

20.3.11 Raisins (Vitis vinifera)

Guadagni et al. (1978b) examined the effect of long-term exposure to insecticidal GLOA treatments on flavor stability of field-run Thompson seedless raisins. After 12 month storage under GLOA (>1 kPa O₂, 9-9.5 kPa CO₂, 86-89 kPa N₂, and 1 kPa Ar) at 15°C and 27°C, raisin flavor, based on taste panel evaluations, was equal or superior to that of raisins stored under normal air.

The effect of a low O₂ atmosphere generated by the addition of a commercial O₂ absorber on fruit color of golden-colored, sultana raisins stored in hermetically heat-sealed gas barrier bags at 15°C, 22°C, and 30°C was assessed over a 28, 56, or 84 day storage period (Tarr and Clingeleffer, 2005). Fruit color changes were measured using the CIE tristimulus L, a, b measuring system. Low storage temperature (15°C) and low O₂ atmosphere both maintained fruit color during the experimental storage regimes. There were significant negative effects on fruit color at the higher temperature (30°C) and longer storage period without a low O₂ atmosphere.

20.3.12 Walnuts (Juglans regia)

Shelf life can be extended by storage in <1 kPa O₂, O₂<0.5 kPa (balance N₂) or CO₂ levels above 80 kPa in air can be effective in insect control (Labavitch, 2004b).

20.4 Conclusions

Low moisture dried fruits and tree nuts are relatively tolerant of many kinds of MA or CA, making their use for insecticidal treatments or for shelf life extension attractive. Although CA treatment times for bulk-stored product are usually much longer than those for methyl bromide, at temperatures >30°C they are often comparable to phosphine fumigation. For applications that do not require rapid turnover of product, such as yard stacks of raisins, CA treatments may be appropriate. Currently, the biggest barrier to widescale adoption of CA for disinfection of bulk dried fruits and nuts is the increased costs, although for high-value organic product, the added cost is more acceptable. MA in packaging (N₂ flushed or vacuum packed) as a means of improving shelf life is currently used, most often by processors of tree nut products.

20.5 Future Research

Much of the cost of CA technology is either building new facilities to house the storage or the costs in building poorly se美元eous, flexible plastic bags. Further research on advancements in the use of AÈ technology may reduce these costs in the future. An important direction for research will be the development of new technologies for insect control. Methods to check the uniformity and ability to use new technologies will also be needed.

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20.5 Future Research Needs

Much of the cost of eA treatments for bulk-stored dried fruits and nuts is associated with either building new gastight storage structures or retrofitting old storage facilities. Gas leaks in poorly sealed storages also drive up the cost. The recent development of inexpensive, flexible plastic containers capable of maintaining treatment gas levels should make the use of CA treatments more affordable. Costs for bulk CA treatment may be further reduced by more fully exploring the use of vacuum under these flexible plastic containers. Further research is needed to integrate this technology with existing processing methods. An important disadvantage to CA bulk treatments is the lengthy treatment times needed for insect control. Treatment at elevated temperatures is well known to decrease treatment times, but may add considerably to the cost or result in product quality degradation. Methods to cheaply apply CA at high temperatures and protect product quality are also needed.

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