Controlling Pests in Dry-Cured Ham: A Review

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Abstract

Dry-cured hams can become infested with ham mites, red-legged beetles, cheese skippers, and larder beetles during the aging process. Though other methods may be used for beetles and cheese skippers, methyl bromide is the only available fumigant that is effective at controlling ham mites in dry-cured ham plants in the United States. However, methyl bromide will be phased out of all industries by approximately 2015. This paper will review and explore potential alternatives that have been investigated to determine their feasibility for replacing methyl bromide to control pest infestations in dry-cured ham plants in the United States. Potential alternatives include: 1) fumigants such as phosphine and sulfuryl fluoride; 2) physical control approaches through cold treatment, modified atmosphere, inert dusts, etc.; 3) pesticides and bioactive compounds; 4) food-grade processing aids. The most promising potential alternatives to date include the use of propylene glycol on the ham surface, the exploration of alternative fumigants, and implementation of an integrated pest management plan.

Keywords: Dry-cured ham, pest management, ham mite, *Tyrophagus putrescentiae*

1. Manufacturing of Dry-Cured Ham

Many types of dry-cured hams are produced around the world. Some of the most popular dry-cured hams are Iberian and Serrano ham from Spain, Corsican ham from France, country style ham from the United States, Westphalia ham from Germany, and Jing Hua ham from China (Toldrá, 2010). American dry-cured ham, also known as country ham, is produced from the hind leg of a pork carcass by rubbing salt and other ingredients that draw out the moisture. A typical American dry-cured ham is treated with salt, nitrate and/or nitrite and loses at least 18% of its original weight during processing. The majority of American dry-cured ham facilities are located in the southeastern states, including Virginia, Kentucky, North Carolina, Tennessee, Georgia, and Missouri (Rentfrow, Chaplin, & Suman, 2012).

Salt, nitrate and/or nitrite are the major ingredients in the cure mix. Salt inhibits the growth of spoilage microorganisms by reducing the water activity and solubilizing some of the myofibrillar proteins. Nitrate is reduced to nitrite and then nitric oxide by nitrate reductase, a natural enzyme in the ham. The typical red/pinkish color of ham is due to the reaction of nitric oxide and myoglobin which forms nitrosyl myoglobin (Toldrá, 2002). Other ingredients such as sugar and black pepper are optional for flavor enhancement. A typical curing mix contains 8 kilograms of salt, 2 to 3 kilograms of sugar, and 90 to 250 grams of sodium nitrate for each 100 kilograms of fresh ham (Ockerman, Basu, Crespo, & Sánchez, 2002). The curing mix is applied on the surface of hams by evenly spreading or hand rubbing at one time or by multiple applications at certain intervals based on the processors' experience and preference (Ockerman et al., 2002). The duration of the ham in the curing mix is typically 6 weeks at 2-4 °C but varies depending on the weight of the fresh ham, the processor's preference and meeting USDA requirements (USDA FSIS 9 CFR 318.10). Salt penetrates hams at an approximate rate of 2.54

cm of cushion depth per week (Marriott & Schilling, 2004). The excess curing mix on the ham surface is removed by washing and soaking hams in water after the curing period. Hams are then transported to a warmer environment (approximately 10-13°C) for approximately 2 weeks for the salt equalization step (Ockerman et al., 2002; Rentfrow et al., 2012).

Aging, also known as ripening, is the processing step that develops the unique and characteristic aroma and flavor of country ham. The intensity of the dry-cured aroma and flavor is a result of extensive lipolysis and proteolysis that are proportional to the length of the aging time. Aging conditions vary based on country of origin (Andres, Ventanas, Ventanas, Cava, & Ruiz, 2005) and individual producers. Aging temperatures usually ranges between 16 °C and 25 °C in Europe with relative humidity between 65% and 80% (Toldrá, 2010). In the United States, the aging temperatures are higher, often greater than 28 °C (Rentfrow et al., 2012). More than 50 % of country hams are aged for 3-6 months (Rentfrow et al., 2012), but there are many companies that age hams between 6 and 24 months to develop intense and desirable flavor characteristics. Hams produced in the Mediterranean area such as Iberian hams are aged for a minimum of 18 months (Ockerman et al., 2002). When aging for a long period, applying a layer of lard on the lean area is a common practice to avoid excessive drying and to prevent cracking and hollow defects (Fulladosa et al., 2010). In addition, minimizing mold growth, covering cracks and holes on the ham with fat and relative humidity control can be used as part of an integrated pest management plan to help control mites.

2. Pest Infestations in Dry-Cured Ham

Dry-cured hams are susceptible to several arthropods, insects and mites during the aging process: ham mites *Tyrophagus putrescentiae* (Acarina: Acaridae), red-legged ham beetles,

Necrobia rufipes (Coleoptera: Cleridae), cheese skippers *Piophilidae casei* (Diptera: Piophilidae) and larder beetles, *Dermestes lardarius* (Coleoptera: Dermestidae).

Tyrophagus putrescentiae (Schrank) (Figure 1), also known as the mold or cheese mite, is a universal species that infests stored food products that have high fat and protein content (Gulati & Mathur, 1995). These products include dried fruits, spices, cultured cheeses (Rentfrow, Hanson, Schilling & Mikel, 2008), pet food (Thind, 2005; Brazis, Serra, Dethioux, Biourge & Puigdemont, 2008), and cereal-based food products (Thind & Clarke, 2001). In dry-cured ham, there is little or no infestation when aging is done for less than three months. However, aging times longer than six months is necessary to obtain the desired flavor and product quality that meets a niche high dollar market. The risk of mite infestation increases when ham is aged for more than five months. However, aging for less than five months does not assure processors that infestation problems will not occur (Rentfrow, Hanson, Schilling & Mikel, 2006). Most mite infestations occur on the surface of food products. However, mites may penetrate inside the product and thus cause more severe economic loss (Zd'árková, 1991). The infested surface sometimes appears to move when observed by the naked eye due to the massive population of mites, and mite dust may appear around an infested food product.

At 60-80% relative humidity and 20-30 °C, the mold mite can complete one generation in 8 to 21 days, and the length of the life cycle increases when the temperature drops (Mueller, Kelley, & VanRyckeghem, 2006). The optimal temperature for females to lay eggs is between 22°C and 26°C. At 20°C and 85%RH, female mites start laying eggs within the first 24 h of mating and are able to lay up to 500 eggs throughout their lives (Boczek, 1991). Once the temperature drops below 10°C, the mites cannot develop, but they are able to survive at 0°C in an inactive state (Mueller et al., 2006). Eggs are more tolerant to adverse conditions such as

fumigation since mites are more active and breathe in fumigant gas, whereas the egg stage has a low level of respiration and is therefore less susceptible to fumigant gasses (Phillips, Thoms, DeMark, & Walse, 2012).

Red-legged beetles (Figure 2) are facultative predators that prey on other insects such as the larvae of corn sap beetles and cheese skippers and cannibals that prey on their own eggs and pupae. Adults are approximately 3.5 to 7 mm long with pale yellowish to reddish colored legs, and a dark blue to metallic green body color (FAO, 1989; Lambkin & Khatoon, 1990; Odeyemi, 1997). Initial infestation is usually due to invasion by adults, which lay their eggs on the surface of the food (FAO, 1989). Larvae hatch and burrow into the food material, seeming to prefer fat. Mature larvae spin cocoons in which they pupate, usually in crevices. Adults feed on the food material but are not as destructive as the larvae. The life cycle varies from 36 to 150 days or more depending on the types of food and temperature. The temperature range of 30-34°C and relative humidity of 50% or above is required for optimum development of *N. rufipes* (FAO, 1989). Adult red-legged beetles may live for more than 14 months, and females can lay up to 28 eggs per day and 3,000 eggs in one life cycle under warm (30° to 33°C) and humid conditions (Roesli & Subramanyam, 2002). Red-legged ham beetles are susceptible to most commonly used insecticides and fumigants.

Cheese skippers (Figure 3), sometimes called ham skippers, are detritivores that are often found on overripe/moldy cheese and salted meats such as dry-cured ham, bacon and beef (Smith & Whitman, 2003). Cheese skippers are small metallic-colored flies that are approximately half the size of the common house fly. Females are slightly larger than males and lay 140-500 eggs on meat and cheese in one life cycle (Lewis & Kaufman, 2011). A complete life cycle from egg to adult ranges between 12 days to a month depending on the nourishment and environmental

conditions. The adult lives for three to seven days (Smith & Whitman, 2003). Once a female oviposits on the food material, the larva, which is the damaging stage, hatches and burrows deeply into the substrate (White, Prendergast, Rosales, Evans & Hogsette, 2006). Mature larvae usually leave the food and crawl into a crevice to pupate. Unintentional human ingestion of cheese skipper larvae can lead to serious accidental intestinal myiasis where the larvae invade the living tissue of humans (Scott, 1964; White et al., 2006).

Larder beetles (Figure 4) are a common pest of cured meats, cheeses, dried fish, dried museum specimens and pet food (FAO, 1989). Adult larder beetles are dark brown in color and have a yellowish band across the front portion of the forewings. The adult is 7-9 mm long and often winters outdoors and enter buildings in the spring and summer. Females lay more than 100 eggs through the summer months and one generation can be completed in 40-50 days under ideal conditions (Jacobs, 2013). The eggs are laid on foods suitable for larval development or in cracks and crevices where such food is stored. Routine inspection and regular sanitation are important to control larder beetle infestations. It should be noted that sanitation is very effective at controlling ham skipper and beetle infestations in facilities that have been built since 2000.

3. Means to Control Pest Infestation in Dry-Cured Ham

3.1 Methyl Bromide Fumigation

Methyl bromide is an odorless, colorless gas that has been used to control pests in commodities and buildings since the 1930s for its broad spectrum application and rapid action (Fields & White, 2002). It diffuses homogeneously within the enclosed space at ambient temperature and is also able to penetrate into pore spaces. Methyl bromide kills mites, insects, nematodes, and microflora rapidly without contaminating the products and is nonflammable and

noncorrosive (Bond, 1984). Methyl bromide's mechanism of action is to damage the membrane of nerve cells in pests (Fields & White, 2002).

The Montreal Protocol is an international treaty signed by the United States and 182 other countries that is designated to protect the ozone layer through phasing out the use of substances that contributes to its depletion (Osteen, 2003). Methyl bromide was listed as a class one ozone depleting substance in 1992 during the third revision. In the United States, approximately 27,000 metric tons (MT) of methyl bromide was used each year prior to 1992. Soil fumigation made up 75% of the total usage, followed by 11% usage for commodity treatments, 6% for structural fumigation, with the remaining percentage for feedstock and industrial chemical production (Johnson, Walse, & Gerik, 2012). The phaseout was scheduled to reduce methyl bromide use by 25% by 1999, 50% by 2001, 70% by 2003 and 100% by 2005 (with the exception of critical use exemptions) (Osteen, 2003). Only yearly requests for critical use exemptions, quarantine and pre-shipment applications, and emergency uses are exempt from the phaseout (Johnson et al., 2012). In 2014, pre-plant strawberries (415MT), post-harvest commodities (0.74 MT), post-harvest structures (22.8 MT), and dry-cured ham (3.7MT) were nominated for critical use exemptions. Dry-cured pork products have received critical use exemptions due to red-legged beetle, ham skipper, dermestid beetle and/or ham mite infestations. When the first methyl bromide consumption reduction began, the price increased from \$2.50/lb in 1999 to \$4.50/lb in 2001 (Osteen, 2003). In 2014, methyl bromide prices exceeded \$20/lb. This increase in price has made it difficult for small processors to afford methyl bromide. Methyl bromide fumigation is important to the economic viability of the dry-cured ham industry in the United States, which has justified the need for research to determine if alternative methods can be developed to prevent and control mite infestations. By definition, dry cured ham is adulterated

in the United States if mites are present at any time during aging (USDA 9 CFR 301, USDA 9 CFR 416). Therefore, even if the presence of mites is a quality problem, US producers are forced to take action to remove mites so that the product is not considered adulterated. Methyl bromide cannot be used to control mites in the European Union. Mites are considered a quality problem in the EU that is controlled through relative humidity, use of lard on the surface, and other good manufacturing practices. The industry and University scientists in the United States are researching potential alternatives to methyl bromide since it is being phased out of use by the industry in the United States. These potential alternatives may include some methods that are currently utilized in Europe to manage mite populations such as the use of hot lard and the control of relative humidity. Since there are no registered effective alternatives for methyl bromide in the United States dry-cured pork industry at this time, the nomination quantity for the United States dry-cured pork industry is 3,240 kg in 2015 (EPA, 2013).

In 2006, thirty-four dry-cured ham processing plants were surveyed (20 plants were both surveyed and audited and 15 plants were only surveyed) in North Carolina (14), Virginia (4 plants), Kentucky (8), Missouri (4), Tennessee (3), and Georgia (1) to determine the extent of ham mite (*Tyrophagus putrescentiae*) and red legged beetle (*Necrobia rufipes*) infestations in dry-cured ham products (Rentfrow et al., 2008). The plants that were audited had between 1 to 4 scientists visit the dry cured ham plant and audit their facility and provide feedback on mite control and to evaluate the extent of infestations in the industry. Sixty three percent of plants (22 out of 34) stated that they use methyl bromide to control ham mite infestations. In addition, approximately half of these plants reported that they use methyl bromide due to red legged beetle infestations. It was approximated that less than 10,000 kg of methyl bromide was used annually by these 34 plants. It was also reported that methyl bromide fumigation occurred from 1 to 5

times per year when used by a plant. Even though the 34 plants that were audited/surveyed are the largest producers of dry-cured pork in the country, results also revealed that there were 30-40 other dry-cured ham producers that use less than a total of 1000 kg methyl bromide per year. Since this time, methyl bromide use by the industry has been reduced to 3000-4000 kg/year due to cost and only using methyl bromide to control infestations, not as a preventative measure (Schilling, Phillips, Aikens,, Hasan, Sekhon, & Mikel, 2010).

Aging times of longer than 5 months cause an increased risk for infestation with mites and beetles (Rentfrow et al., 2008). However, aging for shorter times than 5 months does not assure processors that infestation problems will not occur, and long aging times (≥ 6 months) are necessary to obtain desired flavor and product quality that meets niche markets. From plant audits, it was apparent that methyl bromide was the only method that was effective at controlling mite and red-legged beetle infestations. It was also apparent that preventative measures are being taken to reduce the risk of infestations in both short (< 5 months) and long aged hams (≥ 6 months). All plants with aging periods less than 5 months that did not report infestation problems had aging times of around 3 months, excellent sanitation, and fly control. Excellent sanitation is necessary because ham mites will survive and thrive if facilities are not completely cleaned and sanitized. However, some plants with excellent sanitation and fly control still have infestations. In addition, processors have stated that they have used ozone and phosphine to control ham mites but have not been effective (Edwards and Scott, 2010).

3.2 Researches in Search of Methyl Bromide Alternatives in the United States Since 2007

3.2.1 Laboratory Tests in Search for Methyl Bromide Alternatives

Prior to 2007, minimal research had been reported on the use of methyl bromide alternatives to control pest infestations in dry-cured pork. Since that time, research has been

conducted on the efficacy of using sulfuryl fluoride, phosphine, carbon dioxide and ozone to control ham mites and red-legged beetles under laboratory conditions. Sulfuryl fluoride (SF) was registered for use in processing facilities that produce dry-cured ham in the summer of 2005 (EPA, 2005). In laboratory testing, SF was effective at killing all life stages (egg, larva pupa and adult) of the red-legged ham beetles at below the label rate (31.2 g/m^3), but was ineffective against the egg stage of the ham mite at 20-22 °C, even when applied at three times the label rate (Phillips, Hasan, Aikens, & Schilling, 2008). Fumigation with SF also imparted low residual concentrations of SF and fluoride that are below the established limits by the EPA of 0.2 ppm and 20 ppm, respectively (Sekhon, Schilling, Phillips, Aikins, Hasan, & Mikel, 2010b). Because greater than three times the SF label rate (100 g/m^3) was effective at killing only 95 % of ham mite eggs (Phillips et al., 2008; Sekhon et al., 2010b), it was reported that SF was not a feasible alternative to methyl bromide for the control of ham mite infestations. More recently, Phillips (2013) reported that SF may be effective at controlling mites at elevated temperatures. Under laboratory conditions, SF was effective at controlling all life stages of ham mites when applied for 48 h at 40° C (Phillips & Schilling, 2013).

Phosphine is the most widely used fumigant alternative for methyl bromide (Fields & White, 2002) due to its easy application, effectiveness, low cost and lack of residual residue (Zuryn, Kuang, & Ebert, 2008). The density of phosphine is 1.17 times that of air, and it is a gas at temperatures above - 88 °C, which makes it disperse well during fumigation (Nath, Bhattacharya, Tuck, Schlipalius, & Ebert, 2011). Phosphine is highly toxic to aerobically respiring organisms, but is not toxic to either anaerobic or metabolically dormant organisms (Nath et al., 2011). Phosphine works as a strong reducing agent in the mitochondrial electron transport chain of aerobically respiring organisms. By disrupting normal oxygen metabolism, it

induces the production of highly toxic 'oxyradicals' and other intermediates (Bolter & Chefurka, 1990). These toxic compounds cause the malfunction of vital enzymes that are essential for metabolism (Zuryn et al., 2008). Ham mites can survive in low oxygen environments. Anaerobic respiration will be triggered since reduced aerobic respiration cannot satisfy the energy demand. Accumulated anaerobic end products cause stress to mites (Mitcham, Martin, & Zhou, 2006). The drawbacks that prevent phosphine from being an ideal fumigant include: slow activity which means a longer fumigation period, the need for a highly sealed enclosure, increased pest resistance, and corrosion to certain metals such as copper (Benhalima, Chaudhry, Mills, & Price, 2004; Collins, Daglish, Pavic, & Kopittke, 2005; Price & Mills, 1988; Zettler, Halliday, & Arthur, 1989).

With phosphine, under controlled conditions (3.7 liter gas-tight jars in controlled environment chambers), 100 % mortality of all life stages of red legged ham beetles and ham mites was achieved with 48 h exposure of 400 and 1000 ppm of phosphine, respectively (Schilling et al., 2010; Sekhon, Schilling, Phillips, Aikins, Hasan, Corzo & Mikel, 2010a). In addition, residual phosphine concentrations in dry-cured hams that were fumigated for 48 h at 1000 ppm were below 0.01 ppm, the legal residual limit in stored food products (Sekhon et al., 2010a), and consumer panelists could not detect differences between control and phosphine fumigated samples at 1000 ppm. Sekhon et al. (2010a) reported that phosphine fumigation caused the formation of alpha farnesene, a compound with a sweet, fruity odor. These researchers concluded that phosphine fumigation should be evaluated at the plant level to determine its effectiveness and economic feasibility in real world applications.

Ozone concentrations of greater than 175 ppm for 48 h were able to achieve 100 % mortality of all life stages of ham beetles and mites at the bench top level (Schilling et al., 2010;

Sekhon, Schilling, Phillips, Aikins, Hasan, Nannapaneni & Mikel, 2010c). However, ozone is not able to penetrate surfaces well and therefore may not work well in real world applications since ham mites could potentially penetrate into meat surfaces and ham beetles bore through the meat tissue. Use of ozone increased the concentration of oxidation compounds in hams (Sekhon et al., 2010c), but consumers could not determine sensory differences between control hams and those that were fumigated with ozone at 175 ppm for 48 h (Sekhon et al., 2010c).

Mortality of all life stages of mites was achieved at a concentration of 60 % carbon dioxide with 144 h of exposure (Schilling et al., 2010). In addition, a carbon dioxide concentration of > 80 % with an exposure time of 144 h was necessary to cause 100% mortality for all life stages of red legged ham beetles (Schilling et al., 2010). However, fumigation with carbon dioxide would not be practical since 144 h at a high concentration would require that the plant close longer than 48 h, interrupting the production process. People would also be working in close proximity to the ham houses during fumigation, which could potentially lead to unsafe working conditions.

3.2.2 Food-Grade Coatings as Processing Aids

Coating hams with vegetable oils or hot lard is a common practice in Spain to control mite infestations in dry-cured ham (García, 2004). Some vegetable oils (include coconut, sunflower, groundnut palm, corn, sesame) are used to protect cured fish from pests and to give fish a more attractive appearance (Rajendran & Hajira, 2005). A list of animal and vegetable oils (including soybean oil, canola oil, corn oil, olive oil, mineral oil and lard), sorbic salts (sodium/potassium/calcium sorbate, propionic salts (sodium/potassium/calcium propionate), iodide salts (sodium/potassium/calcium iodide), citrate salts (sodium/potassium/calcium citrate), short chain alcohols (1,2-butanediol, 1,3-butanediol, 1,4-butanediol, 1,2-propanediol, 1,3-

propanediol, 1-propanol, 2-propanol), organic acids (including maleic acid, citric acid, 3,3-thiodipropionic acid) and butylated phenol preservatives (BHT and BHA) have been tested as dippings on dry-cured ham cubes (Abbar, Schilling, & Phillips, 2012). For food dips, 2.5 cubic cm cubes of dry-cured ham were dipped into a test compound of a given concentration for 1 minute and then placed in a ventilated glass jar and inoculated with 20 adult (mostly female) mites. Jars were held for 14 days to allow for mite reproduction and population growth, after which the total number of mite adults and nymphs were counted and compared to numbers produced on other treated ham pieces and on control hams dipped in water only (Abbar et al., 2012). Ham cubes dipped in water produced about 600 mites per jar from 20 parents. Among all of the tested substances, 100% lard, 50% propylene glycol (1, 2-propanediol) and 10% butylated hydroxytoluene (BHT) were effective at controlling mite reproduction under laboratory conditions (Abbar et al., 2012).

Coating hams with hot lard is a common practice in Spain. One concern about this application is that lard may not be permeable to moisture and thus extend the drying and aging time. However, Sanchez –Molinero and Arnau (2014) reported that the application of a small amount of oil drip from lard increased moisture loss in the *semimembranosus* muscle and did not affect the moisture content of the *biceps femoris* muscle. Therefore, coating the ham surface with lard should be evaluated further for its efficacy at controlling mites on American country cured ham. American dry-cured ham products need to lose at least 18% of their original weight during the production process. Therefore, the water vapor permeability (WVP) of the coatings must be considered. A preliminary test on WVP was carried out by coating whole hams with different coatings and the weight loss of each ham was recorded after 48 days in simulated aging houses (Zhao et al., 2014). The coating treatments were: control, 100% propylene glycol, 2%

carrageenan (kappa and iota mixture) +50% propylene glycol, hot lard dip, and diatomaceous earth. Kappa and iota carrageenan were solubilized in propylene glycol and water by heating the mixture to 90 °C. The solution was then cooled to 60 °C and applied to the ham surface. Six hams were utilized for each treatment, and hams were then aged for 42 days. Compared with control hams which had an average of 7.4% weight loss after 48 days, hams treated with 2% carrageenan+50% propylene glycol lost 6.4% of weight. Hams coated with a thin layer of lard lost 5.3% of their original weight. Lard will extend the aging time as a moisture barrier. In Spain almost all hams are aged for over a year. However, in the United States, greater than 50 % of country hams are aged for 3-6 months, and half reported the presence of mites (Rentfrow, Chaplin, & Suman, 2012). Future studies are needed to investigate the potential of treating hams with hot lard application in the United States since it has been reported that this technology effective at controlling mites in Spain. If this technology can be transferred to the Industry in the United States, it could improve the ability of processors to control mite infestations.

Propylene glycol has been used as a humectant in soft-moist dog foods and has been reported to be effective at controlling mite infestations (Aldrich, 2014). Food grade coatings made from polysaccharides and propylene glycol were applied to ham cubes and were effective at controlling mite infestations under lab conditions at 24° C and 50 % RH (Zhao, Abbar, Phillips, & Schilling, 2014). All coating treatments with PG were effective at controlling mite reproduction. This was evident since the control ham cubes had approximately 300 mites on each ham cube at fourteen days after inoculation and the cubes with coating treatments contained 0 mites on each ham cube at fourteen days after inoculation. These results differ from those of Guerrero and Arnau (1995), who reported that propylene glycol has no repellent effect on mites when 200 mites were placed on a ham slice in which half was treated with propylene glycol and

half was untreated. In this study, mites did not differ in their orientation to the two halves of the ham slice. These authors also reported that 14 compounds had a 100 % repellent effect against mites, including numerous essential oils such as citral, cresol, eugenol, and geraniol. In order to reduce the cost of the food grade coating by minimizing the amount of propylene glycol, polysaccharides were used to form uniform and consistent film coatings on the surface of ham cubes (Zhao et al., 2014). Xanthan gum, agar, propylene glycol alginate, and carrageenan+propylene glycol alginate were tested by using proprietary formulations with water and 50% (w/w) of propylene glycol. Coatings were applied by dipping the cubes into the gel solutions. Twenty large (mostly adult female) mites were placed on each cube of ham, and the cube was placed in a mite-proof, ventilated glass container and incubated for 2 weeks. All treatments with 50% PG were effective at controlling mite reproduction. Sensory panels suggested no difference between coated and control hams. Further studies are needed to explore the efficacy of propylene glycol at controlling mite infestations in commercial ham processing plants. These coatings are currently being tested in both simulated aging houses and 4 dry-cured ham facilities to determine if it is possible to scale up this technology.

3.2.3 Commercial Applications of Phosphine

In one experiment, 29 cubic meter containers (simulated aging houses) that contained ham mite and beetle assays and dry-cured hams that were inoculated with mites and beetles were fumigated using Magtoxin (magnesium phosphide cells that quickly generate PH_3) at levels between 1000 and 2800 ppm phosphine. The mite mortality was 99.8 % in the bioassays at two weeks post fumigation when 2000 ppm phosphine was achieved, but not all eggs on either the hams or in the bioassays was controlled, even at concentrations as great as 2000 ppm (Zhao, Phillips, Aikens, Abbar, Amoah, Mikel, & Schilling, 2012). Two fumigation trials were

conducted at a commercial ham aging house with a 2000 ppm target concentration for 48 h. Mite mortality inside bioassay jars was evaluated three weeks post fumigation. There was no visible mite activity on hams or on other visible surfaces for approximately one month after fumigation as compared to a normal period of 3 months during this time of year when MB is used. No living mite was detected from the first fumigation trial; however, live mites were detected in the mite bioassay jars 3 weeks post fumigation in the second trial. Phosphine residue was below the 0.01ppm legal limit and trained panelists could not determine differences between phosphine treated dry-cured hams and non-fumigated hams. Severe electrical damage was discovered within 30 days that was apparently caused by the fumigation (Phillips & Schilling, 2013). Copper fittings from the phosphine fumigated rooms were corroded. In addition, more than \$28,000 in electrical damage was discovered within 1 month after fumigation that was apparently caused by the fumigation.

3.3 Physical Control Methods

Physical methods to control pests in storage commodities include light, temperature, microwaves, ionizing radiation, inert dust, controlled atmosphere, etc. Temperature control such as cold treatments can be applied as part of an IPM program for stored products. The population of most pests of durable products starts to decline slowly at 10°C due to ceased reproduction. However, cooling can only delay the growth of mites and does not provide complete control. At -15°C, most pest species in durable commodities will be controlled after a few days (UNEP, 2001). Cold treatments can be combined with other treatments. One study indicated that ham mite eggs will be killed in less than 24 h at -15°C and 24 days at -5°C (Boczek, 1991). Other researchers stated that freezing at -28 ° C for 48 h did not kill the eggs (Arnau & Guerrero, 1994). A more recent study suggested that 90 % of all mite stages of *T. putrescentiae* can be controlled

through exposure to -18 ° C for 5 h (Eaton & Kells, 2011). However, repeated freezing and thawing will undoubtedly affect the sensory properties of dry-cured ham. Heat treatments have fast action without undesirable residues; however, dry-cured pork will be damaged by high heat and therefore cannot be treated. Mites can also be removed by brushing manually with hot water. However, this requires increased labor and does not control the source of the mites.

Irradiation can be used to eliminate pathogenic organisms in meat products (Cava, Tárrega, Ramirez, Mingoarranz, & Carrasco, 2005). Pests have different sensitivities to irradiation. For example, fruit flies are more sensitive than beetles while mites and beetles are more sensitive than moths. The use of irradiation to control pests is limited since insects are generally damaged and unable to reproduce yet remain alive for weeks after treatment. Although the operation costs of irradiation are low, the capital investment is high and the infrastructure to facilitate commercial irradiation is required. In the United States, the majority of country ham producers are family owned, small meat processors which most likely do not have the capital resources to irradiate their product (Rentfrow et al., 2012). A microwave method patent to control mites in dry-cured ham was developed. A combination of power (50 watts to 1000 watts) and time (15 seconds to 600 seconds) was applied to dry-cured ham without exceeding 40 °C on dry-cured ham at any point, which did not significantly affect the sensory quality of dry-cured ham (Flores, Lorenzo, & Caltala, 1989). Ultrasound can be installed as a repellent that prevents mites from entering the facility (Lemus, 2014). Ultraviolet C irradiation causes death to all life stages of mites including eggs by damaging their nucleic acids. However, the cost of installation limits its application (Lah, Musa, & Ming, 2012; Lemus, 2014).

Modified atmospheres control pest infestations by reducing oxygen content. The advantages are minimal food safety issues and lack of residues in food. There were no visible

mites on hams that were processed in a reduced oxygen ($O_2 < 4.5\%$) atmosphere after 275 days when mites were detected on control hams (Sánchez-Molinero, García-Regueiro, & Arnau, 2010). When reduced oxygen ($O_2 < 4.5\%$) was combined with low relative humidity (50%-60%), the growth of bacteria and fungi on ham surfaces were slower than the control (resting in air with RH 70%-80%). This method may not be feasible since it would be challenging to adapt the conditions in the aging room, and the low concentration of oxygen and/or relative humidity would likely alter the flavor of the hams. Lorenzo and Flores (1988) and Guerrero and Arnau (1995) reported that N_2 exposure at 1 atm was ineffective at controlling mites. These authors also reported that CO_2 exposure for 48 h at 1 atm was effective against mobile life stages of the mite at levels nearing 100 %, but that some eggs were able to withstand CO_2 levels nearing 100 %. Lorenzo and Flores (1988) and Arnau and Guerrero (1994) demonstrated that CO_2 was effective at controlling mites when utilized in conjunction with a pressure of 20 Kp/cm² for 60 min, and that N_2 exposure was effective at controlling mites at a pressure of 60 Kp/cm² for 48 h. In addition, Flores et al., (1989) reported that an atmosphere containing 2 % SO_2 was effective at controlling all mite life stages at 20-25 °C.

3.4 Other Alternatives

Commercial residual pesticides were tested by exposing mites to treated surfaces. Among the tested pesticides, Centynal®, Phantom® and Storcide II® showed promising control on mite populations (Abbar, Zhao, Schilling, & Phillips, 2013). Further trials are needed to evaluate if pesticides are applicable by spraying the ham aging environment before hams encounter mites. Many synthetic pesticides and organophosphate acaricides are recommended to control storage mites; however, they are restricted for use on non-contact food surfaces due to residue concern (Sánchez-Ramos & Castañera, 2003).

Mite control agents that contain plant derived bioactive compounds may be potential alternatives as well. Kim, Kim & Ahn (2004) tested the acaricidal activity of cinnamaldehyde and its 11 derivatives against adults of *T. putrescentiae* with a direct contact method and found that the lethal dose (LD50: concentration to kill half the population) of cinnamylacetate (0.89 $\mu\text{g}/\text{cm}^2$), cinnamaldehyde (1.12 $\mu\text{g}/\text{cm}^2$) and five other congeners were much lower than the commonly used pesticides benzyl benzoate (10.03 $\mu\text{g}/\text{cm}^2$) and DEET (13.39 $\mu\text{g}/\text{cm}^2$). Lee et al (2006) tested the acaricidal activities of fennel seed oil derivatives against *T. putrescentiae* adults using a direct contact method. Compared with benzyl benzoate (11.24 $\mu\text{g}/\text{cm}^2$), the LD50 of fennel seed oil (+)-carvone was 4.62 $\mu\text{g}/\text{cm}^2$. Macchioni et al (2002) studied the acaricidal activity of the main components of pine essential oils against *T. putrescentiae* and found that all the essential oils showed good efficacy, especially 1,8-cineole and limonene which had 100% acaricidal activity through aerial diffusion. A piece of Parma ham harboring more than 20 mites was placed in a 6-cm petri dish, and 6 μL of 1,8-cineole resulted in 100% acaricidal activity. Sánchez-Ramos and Castañera (2000) tested 14 monoterpenes and 7 of them were effective against the mobile stages of *T. putrescentiae* by vapor action. However, none of them were effective against eggs. When applying these bioactive compounds on dry-cured hams, one major concern would be how they would affect the sensory quality of dry-cured hams since they all have distinct aromas that are not distinctive of dry-cured ham flavor.

Cheyletus eruditus is a mite predator, biocontrol agent that shows great potential to control mite infestations in grains and seeds during storage (Zd'árková, 1998). The performance of *C. eruditus* is influenced by temperature, relative humidity, and predator-prey ratio (Lemus, 2014; Zd'árková, 1998). The results of predatory mites for pest control in dry-cured ham was not as satisfactory as in grains (Escudero & López, 2001). The application of certain fungi on the

ham surface may also be a potential method that can be evaluated for its efficacy at controlling mites.

3.5 Integrated Pest Management

The concept of Integrated Pest Management (IPM) is defined by the FAO Panel of Experts as “a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest population at levels below those causing economic injury” (Kogan, 1998). The main focus for an IPM program to succeed is prevention, which includes using physical barriers to prevent insects from entering, frequent cleaning and sanitation, and controlling the environmental temperature and humidity. Another key focus of IPM is to monitor pest populations and to make sure that the preventive actions are effective through inspections. Since 2008, most ham producers in the United States only fumigate when mite infestations are visually observed. Recently, the KSU (Kansas State University) trap (Figure 5), made from a disposable plastic Petri dish with ground dog food was developed to detect and monitor mite populations in dry-cured ham processing plants. Twenty traps were evenly distributed at 3 different ham processing plants. Results suggested that certain areas of the facilities had higher mite activity than other areas and the mite population would increase slowly after methyl bromide fumigation (Amoah, Schilling, & Phillips, 2013). The ability of the traps to detect and monitor mite population dynamics at different trap positions could be a tool for decision-making as to when and what control measure should be implemented at any given monitoring period. For instance, if only a few traps at particular locations consistently capture mites, it may be advisable to identify potential sources of infestation around these traps and clean those areas. This could help avoid the need to fumigate or clean the entire aging room.

The development of a trap that is highly sensitive to monitoring the mites will give a good tool for IPM decisions. Findings suggested that placing the KSU trap along the wall in a fully lit room could result in a high trap capture because the mites tend to use the walls as a guide and also seek refuge in or under the trap when there is light. When the trap was enhanced with violet or ultra violet light emitting diode, LED, more mites were captured. However, the mites avoided traps with red, yellow, or green LEDs (Amoah and Phillips, 2015). Ongoing studies are attempting to correlate mite trap capture with known or estimated mite populations of different sizes under controlled conditions. Ultimately, mite trapping and accurate population size estimates can be correlated with given action levels of mites that can be recognized before one can visually determine that mites have infested a facility.

One aspect of IPM is temperature and humidity control. The optimal temperature for female mites to lay eggs are + 22°C to 26°C and the total number of eggs/female increased significantly when temperature increased from 9°C to 26°C. In addition, females stop laying eggs when relative humidity is below 62% (Boczek, 1991). When the temperature drops below 15°C or increases above 25°C, the relative humidity needs to be higher than 60% for mite development (Boczek, 1991). Thus, controlling temperature and relative humidity in the aging houses to suppress mite reproduction and development are a very important part of an IPM program.

Rentfrow et al (2008) suggested a list of good manufacturing practices to country ham processors for preventing pest infestations, such as 1) a gravel dead zone (no grass or shrubs that can harbor pests) at least 2 feet immediately around the aging house; 2) keep the space outside the plant free of garbage and debris and keep the outdoor trash away from the aging house; 3) keep areas inside the ham plant clean and sanitized; 4) regularly clean the walls and floors of the aging house so that the moisture and fat accumulated on those surfaces will not harbor mites; 5)

personnel who discover mite infestations should change clothes and shower to avoid cross contamination; 6) clean and sanitize the aging house and racks thoroughly at the end of each aging period prior to hanging a new batch of hams.

When the preventive techniques fail to prevent or control pest infestations and the monitoring system suggests that the threshold was met, it would be time to take actions for treatment. It is also important at this step to determine why the preventive technique failed and determine if the relative humidity, mold growth or some other parameter contributed to reaching the threshold. So far the most effective way to control mite infestations and prevent adulteration of the product (USDA 9 CFR 301, USDA 9 CFR 416) in the United States is methyl bromide fumigation. If the aging houses could be well sealed and the electrical devices could be removed or protected, phosphine could be considered a potential alternative to control mite infestations

4. Conclusions

Preventive Integrated Pest Management (IPM) approaches such as sanitation, regular inspection, use of mite traps, and temperature and humidity control should be carried out in dry-cured ham plants as a means to minimize pest infestations. Though phosphine was successful at controlling mites under laboratory conditions and had moderate success at controlling mites under commercial conditions, it was highly corrosive in the ham plant. It would therefore need significant modifications from the previous commercial studies prior to use in ham plants. Food grade coatings that are made from propylene glycol and polysaccharides were effective at controlling mite infestations under laboratory conditions. Therefore, further studies need to be conducted to determine if these coatings can be scaled up for use in commercial settings. In addition, continued research is needed to determine how dry-cured pork producers can control

Tyrophagus putrescentiae infestations since methyl bromide may eventually be unavailable for use by the industry in the United States.

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771 Figure 2. Adult red-legged ham beetle

772 (http://commons.wikimedia.org/wiki/File:Necrobia_rufipes.jpg).

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Figure 3. Adult cheese skipper on cheese

(http://entnemdept.ufl.edu/creatures/urban/flies/cheese_skipper.htm).

Figure 4. Adult Larder Beetle

(<http://www.ozanimals.com/Insect/Larder-Beetle/Dermestes/lardarius.html>).

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828 Figure 5. The KSU mite trap closed (left), and opened, revealing pet food bait and mites.

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