# Effects of fat content, aging time, and additive application methods on the quality characteristics of irradiated ground beef

by

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## ABSTRACT

The effects of fat content, aging time and additives application methods on color, lipid oxidation and volatiles of irradiated ground beef were determined. Two different methods, mixing or spraying, of applying ascorbic acid, α-tocopherol, and sesamol; ground beef with 3 different aging times; and ground beef with 3 different fat contents were used in the study. Beef patties were prepared, treated with additives, placed on Styrofoam trays, wrapped with oxygen permeable plastic film, treated with electron beam irradiation at 0 or 2.5 kGy, and displayed under fluorescent light at 4°C. Color, lipid oxidation, volatiles, oxidation-reduction potential (ORP) and carbon monoxide (CO) production were determined. Irradiation accelerated lipid oxidation, reduced beef redness and produced off-odor volatiles. Beef redness (a* values) was decreased by irradiation without any influence from the application methods, fat contents and aging times. Ascorbic acid was effective in maintaining beef redness after irradiation. Lipid oxidation was accelerated by irradiation regardless of application method or fat content. Aging, however, influenced lipid oxidation where lipid oxidation increased as aging increased. Combinations of ascorbic acid, α-tocopherol or sesamol were effective in slowing down lipid oxidation. Adding sesamol to the combination of ascorbic acid + α-tocopherol made it more effective in slowing down lipid oxidation especially during late storage. Irradiation increased total volatiles production, which was not affected by fat contents. Volatiles aldehydes were tripled in amount as beef aging increased. Beef patties treated with spray application produced more hydrocarbons and alcohols than patties treated with mixing. Ascorbic acid + α-tocopherol was effective in reducing the produced volatiles. ORP were reduced by irradiation without being influenced by fat contents or aging times. Beef treated with mixing application had lower ORP compared with beef treated with spraying. Ascorbic acid + α-tocopherol was effective in reducing ORP. Irradiation increased CO production from beef patties, without any influences from application methods, aging times or fat contents.

# CHAPTER 1. GENERAL INTRODUCTION

Irradiation is among the most effective technologies for controlling pathogenic microorganisms in meat. Ground beef is highly susceptible to microbial contamination, mainly because the way of its preparation. Multiple carcasses are used for ground beef production and having only one contaminated carcass will contaminate the whole batch. So, treating ground beef with irradiation is very important and required process from the safety point of view. However, irradiation has been proven by several studies to change the quality of irradiated meat. Because of quality-related issues, only about 0.15% of produced ground beef in USA is being irradiated (Bruhn and Eustice 2007).

Accelerated lipid oxidation, color change, and off-odor production are the most noticeable quality changes that happen in ground beef as a result of irradiation. Lipid oxidation and color changes are important factors that influence the acceptability of meat and meat products (St. Angelo and others 1990; Hunt and others 1999). Irradiation accelerates lipid oxidation, which consequently will deteriorate odor and color of ground beef (Nam and others 2003; Nam and Ahn 2003). Irradiation, also, changes beef color into unattractive brown or greenish brown color (Nanke and others 1999). It would be difficult to implement irradiation in larger scale without controlling discoloration problems. Off-odor in irradiated meats is mainly caused by volatile sulfur compounds, which are produced by radiolytic degradation of sulfur-containing amino acids such as methionine and cysteine (Ahn and others 2000b). Irradiation off-odor has been characterized by several researchers as a “bloody and sweet” (Hashim and others 1995), “burned oil”, or “burned feathers” (Heath and others 1990) or “barbecued corn-like” (Ahn and others 2000a). The intensity of irradiation off-odor diminishes over storage period as the sulfur volatiles disappear during storage under aerobic conditions (Nam and Ahn 2003b). Therefore, in order to improve consumer acceptance of irradiated ground beef, all these quality changes should be controlled and/or minimized.

Antioxidants such as free radical terminators or metal chelating agents are commonly used in meat to reduce lipid oxidation and improve sensory quality of meat (Hsieh and Kinsella 1989; Chen and Ahn 1998). Incorporating α-tochopherol in diets is effective to reduce lipid oxidation in meat during storage (Wen and others 1996; Morrissey and others

1997). Ascorbate is a reducing agent that can minimize the oxidation of meat pigment and prevent color changes. Combining ascorbate and tocopherol is effective in preventing both color change and lipid oxidation in ground beef (Nam and others 2003; Nam and Ahn 2003). Aerobic packaging is an effective way to control irradiation off-odor, but increases lipid oxidation. Double-packaging, in which both aerobic and vacuum packaging are combined, is an efficient packaging method that has been proven to be effective in minimizing color changes and lipid oxidation and control off-odor production in irradiated turkey and pork (Nam and Ahn 2002).

The goals of this study were to examine how the effects of ascorbic acid and selected antioxidants on lipid oxidation, color change and volatiles production in irradiated ground beef were influenced by the application methods of those additives, aging time of beef, and fat contents of the meat used.

## Dissertation Organization

This dissertation is in an alternative style format consisting of an abstract, a general introduction, a review of literature, three manuscripts for publication, and a concluding summary. The three manuscripts represent the work done by the first author to fulfill requirements for the degree of Doctor of Philosophy. The manuscripts were prepared according to the journal of food science style guide. Three manuscripts consist of an abstract, introduction, materials and methods, results and discussion, conclusion, and references.

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# CHAPTER 2. REVIEW OF LITERATURE

## Lipid Oxidation in Meat

Oxidative rancidity is a major cause of meat deterioration during the storage of meat and meat products (Gray and others 1996). Flavor deterioration of meat is caused by the breakdown products of lipid oxidation such as carbonyl compounds, hydrocarbons, and furans (Ladikos and Lougovois 1990; Murano 1995). Lipid oxidation occurs through free radical chain reactions, and oxygen is an important factor in the development of lipid oxidation (Ahn and others 1993). Several factors, including pre-slaughter, post-slaughter and processing factors influence the rate and extent of lipid oxidation in muscle tissues. During processing various factors can influence lipid oxidation in meat and meat products: composition of raw meat, aging time, cooking, size reduction processes such as grinding and emulsification, deboning, additives such as salt, nitrite, spices, and antioxidants, temperature abuse during handling and distribution, oxygen availability, and prolonged storage (Kanner 1994; Rhee 1988). Warmed over flavor is a frequently used term to describe unpleasant flavor of reheated cooked meat associated with oxidation (Love and Pearson 1971; Asghar and others 1988). Because of the free radical chain reactions any degree of lipid oxidation in raw meat accelerates the development of oxidized off-flavors in cooked meat (Rhee 1989). Ahn and others (1992) reported that because of the damage in phospholipids structure as a result of cooking, the rate of oxidation is faster in cooked meat compared with raw meat. Thiobarbituric acid reactive substances (TBARS) method is frequently used to measure malonaldehyde content, which is a secondary oxidation product of polyunsaturated fatty acids, in meat. Also, hexanal, an oxidation product of linoleic acid, was used as indicator of lipid oxidation (Melton 1983). Ang and Lyon (1990) found that intensities of warmed over, rancid, cardboard, and overall off-flavor characteristics increased with the increase of TBARS and headspace aldehydes contents. Additionally, TBARS values and propanal, pentanal, hexanal and total volatiles in pork were highly related. Meat cuts affected lipid oxidation and oxidative products of pork during frozen storage at -10° C, where pork belly cut had higher TBARS and pH values compared with loin (Park and others 2007). All forms of iron catalyze lipid oxidation of beef extract whether it was aqueous or chloroform/methanol extraction, and both TBARS and peroxide values increased by heating

(Han and others 1995). High level of oxygen in MAP (80% $O_2$/20% $N_2$) increased lipid oxidation and protein oxidation in minced beef patties stored for up to 6 days in the dark at 4° C (Lund and others 2007). TBARS values and heme iron contents are different among different meat species. Frozen raw beef and pork had higher TBA and heme iron content than those of chicken, whereas for cooked samples, chicken thigh muscles, which have the highest polyunsaturated fatty acid, had the highest TBA values compared with other species regardless of the storage temperature (Rhee and others 1996). Oxidation flavor and rancidity in cooked meat were mainly caused by aldehydes with hexanal being the predominant one (Shahidi and Pegg 1994). Lee and Ahn (2003) found that TBARS values of irradiated oil emulsion samples were lower than those of nonirradiated ones, however, after 10 d of storage at 4° C irradiated samples had higher TBARS values compared with nonirradiated samples. Aldehydes such as hexanal and propanal were the most among volatiles to increase because of irradiation. Arachidonic acid was the main source of hexanal while propanal was produced mainly from linolenic acid.

## Lipid Oxidation in Irradiated Meat

Ionizing radiation would produce hydroxyl radicals and generate lipid oxidation-induced off-odor in meat. Oxidative changes induced by irradiation are dose dependent and the presence of oxygen is an important factor in the development of oxidation and odor intensity (Merritt and others 1975; Katusin-Razem and others 1992). Luchsinger and others (1996) found that irradiated vacuum-packaged boneless pork chops were less rancid compared with aerobic-packaged chops. At irradiation dose of 1.6 kGy, lipid oxidation of sliced ham and all-pork frankfurters stored for eight weeks at 2° C to 4° C were not different from nonirradiated controls (Houser and others 2005b). At a higher dose of irradiation (e.g., 4.5 kGy), lipid oxidation increased in all irradiated vacuum-packaged cured ham over 90 days of storage at 2° C to 4° C compared with nonirradiated controls (Houser and others 2003). Irradiation at 1.5 to 10 kGy dosage increased TBARS values in aerobically packaged turkey breast muscles (Ahn and others 2001).Gamma irradiation significantly increased total *trans* fatty acids in ground beef and that increase was irradiation dose-dependent. Ground beef irradiated at the highest dose, 7 kGy, had the highest total *trans* fatty acids, total monounsaturated and total unsaturated fatty acids compared with the other irradiation treatments, 0, 1, 3, 5 kGy. Also, irradiation altered the ratio of total unsaturated fatty acids to total saturated fatty acids where it was 0.85, 0.86, 0.87 and 0.89 at irradiation dose of 1, 3, 5, and 7 kGy, respectively, compared with 0.85 in for nonirradiated controls (Yilmaz and Gecgel 2007). Lipid oxidation of ground beef irradiated at 2 kGy was not affected by neither packaging, vacuum or aerobic, nor irradiation conditions (irradiated vs. nonirradiated) during one week of storage period at 4° C (Murano and others 1998). Normal and pale-soft-exudative (PSE) muscles were more susceptible to lipid oxidation, caused by irradiation and storage, than dark-firm-dry (DFD) muscles (Nam and others 2001). TBARS values of both chilled and frozen boneless pork chops were stable, regardless of display day, dose and irradiation sources (Luchsinger and others 1997). Ahn and others (2000a) reported that the TBARS of irradiated vacuum-packaged pork patties was similar to those of nonirradiated ones. However, the TBARS values of aerobically packaged patties increased with irradiation. Lipid oxidation in irradiated cooked meat is a bigger problem if meat is stored under aerobic than vacuum conditions (Merritt and others 1975; Ahn and others 1997).

The availability of oxygen is one of the most important factors for the development of lipid oxidation in both raw and cooked meat (Ladikos and Lougovois 1990). Meat and meat products could be protected from oxidation by excluding oxygen, which will lead to blocking the initiation step of the chain reaction (Ahn and others 1992; 1993; 1995). Diehl (1995) reported that hydrogen peroxide is produced as a result of irradiation of aqueous systems in the presence of oxygen. Ahn and others (1998a) found that avoiding oxygen exposure after cooking played more important role than packaging and irradiation in the development of lipid oxidation. Irradiation before cooking did not affect lipid oxidation of cooked pork during storage (Chen and others 1999).

## Control of Lipid Oxidation in Meat

To reduce lipid oxidation in meat, free radical terminators or metal chelating agents are commonly used (Hsieh and Kinsella 1989; Chen and Ahn 1998). St. Angelo and others (1990) found that both free radical scavengers and metal chelators were capable of inhibiting warmed over flavor (WOF) in beef. Lee and others (2003) reported that far infrared-treated rice hull extract was effective, as antioxidant, in controlling rancidity of irradiated raw and cooked turkey breast meat. TBARS values and volatile aldehydes (hexanal, pentanal, and propanal) were significantly decreased. The antioxidant activities of 0.1% rice hull were similar to that of 0.01% sesamol or 0.1% rosemary oleoresin. The only two disadvantages of using the rice hull extract were an increase in red and yellow color intensities and the production of an off-odor characteristic to rice hull in meat. Sebranek and others (2005) found that the antioxidant effectiveness of rosemary extract at 2,500 ppm was equal to that of butylated hydroxyl anisole (BHA)/butylated hydroxyl toluene (BHT), at permitted concentrations, when used in refrigerated fresh and precooked-frozen pork sausage. In frozen sausage, the effect of rosemary extract was even superior to BHA/BHT. Rosemary extract was effective in maintaining low TBARS values. Also the pork flavor score, reported by the panelists, was higher in sausages treated with 2,500 ppm rosemary extract compared with control and a lower (1,500 ppm) rosemary concentration treatments.

Lipid oxidation in irradiated beef was significantly reduced by adding 0.1% ascorbic acid or sesamol + α-tocopherol, 0.01% each. The antioxidant effect of sesamol + α-tocopherol was stronger than that of ascorbic acid, specially, during the late period of the storage (Ahn and Nam 2004). Raisin paste was effective in lowering TBARS values in cooked ground beef, pork and chicken stored at 2° C for up to 14 days. Sensory panelists evaluated samples for meat flavor intensity, rancid flavor intensity and raisin flavor intensity, and gave lower scores for rancid flavor for those samples treated with raisin paste. Minimum raisin concentrations that showed the highest antioxidant effect were 1.5%, 2.0%, or 2.0% in cooked ground beef, pork, or chicken, respectively. TBARS values and rancid flavor scores were highly correlated. Additionally, treating meat samples with reducing sugar, glucose, was as effective as treating them with raisin paste in term of lowering TBARS values and rancid flavor scores by panelists (Vasavada and Cornforth 2006).

Chitosan alone and in combination with α-tocopherol or rosemary had very intense antioxidant effect in fresh pork sausage stored at 4° C for 20 days. Also, rosemary alone showed a similar intensity of antioxidant activity. Moreover, chitson was capable of extending, almost doubling, shelf life of fresh pork sausages (Georgantelis and others 2007). Wills and others (2007) reported that the incorporation of δ-tocopherol in phospholipids, a polar lipid fraction, using a polar carrier such as ethanol was significantly effective in lowering the TBARS in cooked ground beef. This result indicates that using ethanol changes the target of tocopherol from triacylglycerols into phospholipids which make the antioxidant activity of tocopherol more effective. Lund and others (2007) found that rosemary extract and ascorbate/citrate, as two different antioxidant systems, were effective in preventing lipid oxidation in minced beef patties stored up to 6 days in the dark and caused by high level of oxygen in MAP (80% $O_2$/20% $N_2$).

Using wheat gluten, soy protein and carrageenan coatings and carrageenan film were effective in reducing lipid oxidation in precooked beef patties stored for 3 days under refrigeration, both TBARS values and hexanal content were reduced (Wu and others 2000). Greene and others (1971) reported that adding ascorbic acid, 0.05%, plus either BHA or PG, 0.01% each, to raw ground beef, packaged in oxygen permeable film and stored under refrigeration for up to 8 days was effective in reducing lipid oxidation. Adding α-tocopheryl acetate (vitamin E) to steers diets was effective in controlling lipid oxidation in cooked beef muscle for up to 6 days of storage at 4° C. Vitamin E concentrations in raw and cooked muscles increased as level and duration of supplementation in diet increased, and it was not affected by the cooking (Liu and others 1994). Treating beef with onion or textured vegetable proteins delayed the oxidative rancidity after cooking and storing for 3 days at 4° C. Also in turkey, adding hot-water extracts of eggplant tissues, peels of yellow onions, potatoes, and sweet potatoes were effective in controlling rancidity as well. Panel scores were positively correlated with TBARS values in cooked beef. However, in turkey that wasn't the case where the panelists did not scored rancid meats with low score although of their high TBARS values (Younathan and others 1980). Oxidative stability of cooked ground beef was significantly improved by using the extracts of grape seed and pine bark, 0.02% each. Also, hexanal content were reduced by 97%, 94% and 73%, after 3 d of refrigerated storage, as a result of adding grape seed extract, pine bark extract, and oleoresin rosemary, respectively. Similarly, the WOF scores of the sensory analysis indicated the effect of those extracts in stabilizing oxidative activity and reducing hexanal production. There was a correlation between the three measurements (TBARS values, hexanal content, and WOF scores), which were used to evaluate the antioxidant effects of the added extracts (Ahn and others 2002).

While rosemary, oregano and borage were capable of reducing TBARS formation in beef patties packaged in MAP (70% $O_2$/20% $CO_2$/10% $N_2$) and stored in the dark at 2° C for 24 days ascorbic acid was not. Borage was a strong antioxidant that completely inhibited TBARS formation in the beef patties. Shelf life of beef patties was extended from 8 to 12 day because of these natural antioxidants, as indicated by the sensory analysis. Moreover, adding ascorbic acid to rosemary resulted in extending the shelf life for an additional 4 days (Sanchez-Escalante and others 2003).

A combination of antioxidants (rosemary-tocopherol) and double packaging had lower TRABS values in irradiated pork loins compared with vacuum-packaged, no antioxidants added controls after 10 days of refrigerated storage. Additionally, the production of hexanal, a lipid oxidation-dependent volatile, was effectively reduced by the rosemary-tocopherol combination (Nam and others 2006). A different combination of antioxidants (seamol + α-tocopherol, or gallate + α-tocopherol) and double-packaging (7 days of vacuum packaging followed by 3 days in aerobic packaging) was effective in lowering TBARS values in irradiated turkey breast patties. Lipid oxidation was controlled by antioxidants combinations and vacuum-packaging of the double-packaging (Nam and Ahn 2003b).
Hot vacuum-packaging, in which products were immediately packaged after cooking to eliminate or reduce oxygen contact, was effective, compared with conventional cold vacuum-packaging, in reducing TBARS values in cooked turkey meat patties even after adding prooxidants such as ferrous iron and myoglobin. Also, vacuum-packaging, regardless of being hot or cold, significantly controlled lipid oxidation in cooked turkey meat compared with loosely packaged patties after 1 week of refrigerated storage (Ahn and others 1992).

## Meat Color

Meat color plays an important role in consumer decision to purchase meat, mainly because consumers use meat color as an indicator of meat freshness. Because of surface discoloration, nearly 15% of retail beef is reduced in price and this may cost an annual loss of 1 billion dollars (Smith and others 2000).

Myoglobin is the main protein responsible for meat color where it represents about 70 to 95% of the total pigments in meat, while other heme proteins such as hemoglobin and cytochrome C may also play small role in meat color (Rickansrud and Henrickson 1967; Fox 1987; Judge and others 1989). Oxygenation, oxidation, oxidation plus reduction, and carbon monoxide myoglobin formation are the main four chemical forms of myoglobin that are responsible for fresh meat color. Deoxymyoglobin is the pigment form where no ligand is present at the $6^{th}$ site of the heme iron, and the iron is in ferrous form. This form has a purplish-red color and is associated with muscle immediately after cutting and in vacuum packaged products. The first chemical reaction, oxygenation, happens when deoxymyoglobin exposed to oxygen and the color change to bright cherry red. The pigment at this point called oxymyoglobin and it has oxygen attached to the $6^{th}$ site of heme iron, and the iron still in ferrous form. The second chemical reaction, oxidation, happens when either deoxymyoglobin or oxymyoglobin gets oxidized, the oxidized form of the pigment has brown color and called metmyoglobin. The iron form in metmyoglobin is ferric, and the $H_2O$ is attached to the $6^{th}$ site of iron. Among the factors that affect metmyoglobin formation are concentration of mitochondria, mitochondrial enzyme activities, oxygen partial pressure, temperature, and pH (Renerre 1999). The third chemical reaction, oxidation plus reduction, happens when the oxymyoglobin form converted to metmyoglobin first then to deoxymyoglobin. This reaction depends on muscle reducing enzyme systems, muscle's oxygen scavenging enzymes and the NADH. During postmortem storage, the activities of those three factors continuously decrease. Carbon monoxide myoglobin formation is the forth chemical reaction in which carbon monoxide bind to the $6^{th}$ site of iron and form bright red color.

Considerable amount of carbon monoxide (CO) gas was produced as a result of radiolysis of organic component, such as alcohols, aldehydes, ketones, carboxylic acids, amindes, and esters, in irradiated frozen meat and poultry (Furuta and others 1992; Woods and Pikaev 1994). Reactivity of myoglobin toward diatomic ligands such as oxygen, nitric oxide, and carbon monoxide is different. The affinity of CO to ferrous myglobin was 100 times greater than that of metmyoglobin (Hargrove and Olson 1996). The oxidation-reduction potential (ORP) of meat determines the status of iron in heme pigments and increases in reducing power favors CO-Mb complex formation, which intensifies the redness of heme pigments. The ORP of meats decreased after irradiation but increased rapidly after aerobic storage (Hannah and Simic 1985; Nam and Ahn 2002a,b). The affinity of CO to heme pigments reduced by the rapid increases of ORP in irradiated meat under aerobic condition. Although the amount of CO produced and changes in ORP in beef are not much different from those from light meat (Kim and others 2002a), the color of irradiated beef after irradiation becomes brown/gray instead of pink, especially under aerobic conditions (Nanke and others 1999; Nam and Ahn 2003c)

## Color Changes in Irradiated Meats

Various factors such as irradiation dose, animal species, muscle type, and packaging type affect the degree of color changes by irradiation (Nanke and others 1999; Rickansrud and Henrickson 1967; Fox 1987). Satterlee and others (1971) reported that gamma irradiation at low doses converted bovine metmyoglobin with its brown color into a red pigment, which is similar to oxymyoglobin. Houser and others (2005a) reported that the color of aerobic and vacuum-packaged cured ham that was faded as a result of irradiation at 4.5 kGy was regenerated over a period of 7 days storage at 2° C to 4° C. Freshly ground mutton irradiated at 2.5 kGy had better color than nonirradiated controls (Paul and others 1990). The redness of ground beef was significantly decreased by irradiation and the color was changed from bright red to green/ brown depending on the age of meat (Ahn and Nam 2004). Nam and Ahn (2002a) claimed that the formation of CO-heme pigment complex was the cause of the pink color formed in irradiated precooked turkey breast. The claim was based on the fact that irradiation decreased oxidation-reduction potential (ORP) and produced CO. They supported their claim by the reflectance spectra of meat and the absorption spectra of myoglobin solution. At a dosage of 5.0 kGy ionizing irradiation, the color of irradiated chicken breast changed from it usual brown or purple to pink or red color (Millar and others 1995).

Animal species and packaging conditions are among the factors that affect color changes in irradiated meat. Nanke and others (1998; 1999) found that irradiation changes meat color differently in different species. Also, packaging, vacuum vs. aerobic, was a factor in those color changes. Vacuum-packaged pork and turkey meat became redder, while beef became less red and more yellow. Similarly, visual analysis indicated increase in redness for both pork and turkey while beef redness values were decreased as irradiation dose increased. Aerobically packaged pork and beef became less red, whereas turkey meat became redder after irradiation, but, the redness decreased during storage. Irradiation and storage increased the yellowness, b*-values, of all species. Visually, while pork and beef increased in brownness turkey increased in redness as irradiation dose increased. A metmyoglobin-like pigment was induced by irradiation in pork and beef, whereas irradiation did not change the pigment in turkey meat.

Kim and others (2002) reported that irradiation increased the redness of pork loin muscle, and the red color was stable under aerobic conditions during refrigerated storage. Irradiated pork steaks had red color, which was more intense and stable under anaerobic conditions compared with aerobic conditions (Luchsinger and others 1996). The redness value of both aerobically and vacuum-packaged turkey breast were increased by irradiation, but vacuum-packaged meat was redder than aerobically packaged ones and was stable during storage (Nam and others 2002a,b).

## Oxidation-Reduction Potential in Irradiated Meat

Reducing conditions are important for irradiated meat to maintain its heme iron in ferrous form. Metmyoglobin formation happens as soon as the reducing power in meat is exhausted (Ledward 1984). Simic (1983) reported that irradiation shifted the redox properties of irradiated meat toward more reducing conditions. It was proposed that oxymyoglobin-like pigment was formed by the reduction of heme iron by a radiolytic water product, hydrated electron, and the oxygenation from either residual oxygen or generated oxygen during irradiation (Giddings and Markakis 1972). Hydrated electrons (aqueous $e^-$), a radiolytic radical generated in water because of irradiation, can act as a powerful reducing agent where it will react with ferricytochrome and produce ferrocytochrome (Swallow 1984). Irradiation decreased the oxidation-reduction potential in turkey breast, which provided a reduced environment to the meat pigment to be in the ferrous form (Nam and others 2002a,b).

## Off-Odor Volatiles in Irradiated Meat

Off-odor production is another quality change that happens in meat because of irradiation. Several volatile compounds were identified from irradiated meats including carbonyls, hydrocarbon, and sulfur compounds (Angelini and Merrit 1975; Nawar 1986).

Sulfur-containing compounds, such as hydrogen sulfide and methyl mercaptan, are the sources of the undesirable odors produced in beef as a result of gamma irradiation. Water-soluble proteins in meat were suggested to be involved in the formation of those off-odors (Batzer and Doty 1954). Dimethyl trisulfide was the most potent compound that contributed to irradiation odor isolated from irradiated raw chicken, other volatiles such as methyl mercaptan and sulfur dioxide also contributed to the odor (Patterson and Stevenson 1995). At dosage of 3.0 kGy, irradiation increased the production of sulfur compounds such as dimethyl disulfide in breast fillets (Du and others 2001). Irradiation increased the production of sulfur-containing volatiles in normal, pale-soft-exudative (PSE) and dark-firm-dry (DFD) muscles, and normal and PSE muscles had higher total volatiles compared with DFD (Nam and others 2001). Ahn and others (2000b) suggested that volatile compounds responsible for off-odor in irradiated meat were produced by radiolysis of protein and lipid molecules, and were totally different from those of lipid oxidation.

All irradiated meat produced characteristic irradiation odor regardless of lipid oxidation degree. Several sulfur compounds were newly generated or increased in meat because of irradiation such as dimethyl sulfide, dimethyl disulfide and dimethyl trisulfide, and they were responsible for irradiation off-odor in meat (Ahn and others 1997; 1998b; 1999). Sulfur compounds formed by radiolysis of sulfur-containing amino acids might be the major contributors for irradiation odor (Ahn and others 2000b). Jo and Ahn (2000) reported that dimethyl disulfide was formed when methionine was irradiated while carbon disulfide was formed from irradiated cysteine, indicating that radiolysis of amino acids played an important role in volatile formation after irradiation. Sulfur compounds produced by irradiation were highly volatile and evaporated under aerobic conditions during storage but remained in meat during storage under vacuum packaging (Ahn and others 2001).

Ahn and Lee (2002) found that sulfur compounds represented the majority of volatiles produced by irradiation of sulfur amino acids, which indicates high susceptibility of sulfur amino acids to irradiation. Also, they claimed that irradiation-produced free radicals attack the side chains of amino acids at more than one site, and several volatiles, other than sulfur volatiles, are produced by secondary chemical reactions (Ahn 2002). Not only irradiated amino acid samples produced sulfur volatiles but nonirradiated samples produced as well. However, a stronger and more astringent sulfury odor was produced from irradiated samples.

Lee and Ahn (2003) identified volatile compounds produced from individual fatty acids by irradiation and found that the odor characteristics and intensity were not different between irradiated and nonirradiated fatty acid emulsions despite of changes that happened in their volatile profiles because of irradiation. Lipid oxidation was accelerated by irradiation during storage. They also found that volatiles produced by lipid oxidation were responsible for only small part of the irradiation off-odor.

Volatiles produced in meat are influenced by irradiation, storage time, or packaging methods. The production of 3-pentanol, 3-methyl pentane, 2 butanone, 1-octene, octane, 3-octene and hexanal were influenced by irradiation. Those influenced by storage time included pentane, ethanol, dimethyl sulfide, carbon disulfide, 1-propanol, 3-methyl butanal, heptene, methyl thioacetate, dimethyl disulfide and total volatiles were influenced by storage time. Packaging methods influenced the production of butane, propane, mercaptomethane, dimethyl sulfide, hexane, heptane, 2-octene, and hexanal (Ahn and others 2003).

## Control of Quality Changes in Irradiated Meat

Cinnamon, cloves, fennel, pepper, and star anise have antioxidant effects as indicated by lowered TBARS values in cooked ground beef. The lowest concentration for them, except cloves, to be effective as antioxidants is 0.5%, while for cloves only 0.1% is effective. Scores for rancid odor and flavor, as indicated by sensory panelists, were highly correlated with TBARS values. There was, also, an inverse correlation between spice flavor and rancid odor and flavor (Dwivedi and others 2006). Vasavada and others (2006) found that all the 13 ingredients that form an Indian spice blend (garam masala) have antioxidant activities in cooked ground beef when they added individually in certain concentration. Cloves were the most effective spice in controlling lipid oxidation compared with the others (black pepper, caraway, cardamom, chili powder, cinnamon, coriander, cumin, fennel, ginger nutmeg, salt, star anise). Sensory analysis showed that all the 13 spices lowered rancid odor and flavor. TBARS values were positively correlated with rancid odor and flavor.

Ascorbic acid at 0.1% was effective in preventing color change of ground beef from bright red to green/brown, and the effect of ascorbic acid became greater as the age of meat or storage time after irradiation increased (Ahn and Nam 2004). Far infrared-treated rice hull extract was effective, as antioxidant, in controlling off-odor of irradiated raw and cooked turkey breast meat. Volatile aldehydes such as hexanal, pentanal, and propanal were significantly decreased. Also the production of sulfur compounds such as dimethyl disulfide, which is responsible for irradiation off-odor, was reduced (Lee and others 2003). Huber and others (1953) reported that the use of antioxidants such as ascorbate, citrate, tocopherol, gallic esters was effective in reducing irradiation off-odor. Nam and others (2003b) found that using antioxidants was effective in inhibiting the production of hydrocarbons and volatile aldehydes in aerobically packaged beef. Moreover, the amount of dimethyl disulfide was reduced because of using ascorbic acid and sesamol + tocopherol.

Incorporating antioxidants into cell membrane via dietary treatments reduced the extent of lipid oxidation in meat during storage (Winne and Dirinck 1996; Wen and others 1996; Morrissey and others 1997). Irradiated meat from chickens, reared on diets supplemented with α-tocopherol and ascorbic acid, produced similar volatiles patterns but the amount of volatiles were reduced (Patterson and Stevenson 1995). Nam and Ahn (2003a) found that the addition of ascorbic acid with or without sesamol + tochoperol lowered the ORP values in irradiated ground beef regardless meat age. As a result, the lowered ORP maintained meat pigment in the reduced form (ferrous).

Sulfur compounds which are responsible for irradiation off-odor could be eliminated under aerobic conditions (Ahn and others 2001). Double-packaging, in which both aerobic and vacuum-packaging are combined, has proven to be effective in controlling lipid oxidation and off-odor (Nam and Ahn 2003b,c). The greenish brown color of irradiated ground beef was more problematic under aerobic conditions, while vacuum packaging condition was good enough to avoid the development of greenish brown color (Nam and others 2003).

A combination of antioxidants (sesamol + α-tocopherol, or gallate + α-tocopherol) and double-packaging (7 days of vacuum packaging followed by 3 days in aerobic packaging) was effective in reducing sulfur volatiles production and reducing red color formation caused by irradiation in turkey breast patties. Both irradiation off-odor, caused by sulfur volatiles, and red color, caused by CO-Mb, was controlled by aerobic packaging of the double packaging and antioxidants combination (Nam and Ahn 2003b). Another combination of antioxidants (rosemary-tocopherol) and double-packaging was applied by Nam and others (2006). The antioxidants combination alone, without the double-packaging, were not capable of controlling the production of irradiation-induced sulfur volatiles responsible for off-odor and color changes. On the other hand double-packaging, 7 days under vacuum packaging followed by 3 days under aerobic condition, managed to significantly reduce the production of sulfur volatiles. Additionally, the production of hexanal, a lipid oxidation-dependent volatile, was effectively reduced by the rosemary-tocopherol combination.

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# CHAPTER 3. EFFECT OF ASCORBIC ACID AND ANTIOXIDANTS ON COLOR, LIPID OXIDATION AND VOLATILES OF IRRADIATED GROUND BEEF USING DIFFERENT APPLICATION METHODS

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## Abstract

Two different methods of applying ascorbic acid and antioxidants to ground beef were tested in this study. Ground beef were prepared, mixed or sprayed with none, 0.05% (wt/wt) ascorbic acid or 0.01% (wt/wt) α-tocopherol + 0.01% (wt/wt) sesamol or 0.05% (wt/wt) ascorbic acid + 0.01% (wt/wt) α-tocopherol + 0.01% (wt/wt) sesamol, and irradiated at a dosage of 0 or 2.5 kGy using a Linear accelerator. The meat samples were placed on Styrofoam trays and wrapped with oxygen permeable plastic film, and displayed under fluorescent light for 7 days at 4° C. Color, lipid oxidation, volatiles, oxidation-reduction potential (ORP) and carbon monoxide (CO) production were determined at 0, 3, and 7 days of storage. Irradiation increased lipid oxidation, but not significantly. Treatments α-tocopherol + sesamol, and ascorbic acid + α-tocopherol + sesamol were more effective in slowing down oxidation compared with ascorbic acid. Beef lightness and redness were decreased by irradiation. Lightness did not change over the storage period. Redness, however, decreased as storage time increased. Ascorbic acid was the most effective in maintaining the red color of beef followed by ascorbic acid + α-tocopherol + sesamol. Yellowness of beef, also, was decreased by irradiation and over storage period. Irradiation lowered ORP for both application methods, but the reduction was higher in the mixing application. Similarly, ascorbic lowered ORP of nonirradiated beef more in mixing application than spraying. Application methods did not influence the increased CO production by irradiation. Beef sprayed with additives produced more volatiles than the mixing application. Beef sprayed with additive produced more hydrocarbons and alcohols than the mixing application. The three added additives were effective in reducing the volatiles produced by irradiation.

Key Words: Ground beef, irradiation, antioxidants, application methods, meat quality

## Introduction

It has been estimated that in US ground beef products represent about 44% of the total fresh beef available for consumption (Breidenstein and Williams 1986). Meat color is one of the parameters that determine and affect consumer purchasing decisions. In retail cases, displaying meat under high-intensity lights accelerate the formation of metmyoglobin with its unattractive brown color (Faustman and Cassens 1990). Because of meat discoloration retailers lose more than a billion dollars every year (Hermel 1993). Irradiation negatively changes ground beef color by developing undesirable greenish or brownish gray color (Nanke and others 1998; Kim and others 2002a; Nam and Ahn 2003a).

Unlike popular belief, ground beef oxidizes faster than ground pork or poultry (Nam and others 2001; Kim and others 2002a). Under aerobic condition, irradiation accelerates lipid oxidation in fresh raw pork and beef patties despite of their intrinsic antioxidant activities (Ahn and others 1998a,b; Kim and others 2002b). Oxidative rancidity in food products are commonly measured by the 2-thiobarbituric acid (TBA) test (Melton 1983). There was good correlation between sensory analysis of rancid odor and TBA values in fresh and cooked ground beef (Tarlardgis and others 1960; Poste and others 1986; Brewer and Harbers 1992).

Food antioxidants are used in fresh and further processed meat to prevent oxidative rancidity and improve color stability (Xiong and others 1993; Morrissey and others 1998; Sanchez-Escalante and others 2001). Some phenolic antioxidants such as vitamin E have free-radical-scavenging properties and stop free-radical reactions in meat during storage (Gray and others 1996; Morrissey and others 1998). Therefore, the combinations of phenolic antioxidants such as gallate, sesamol, and tocopherol, were effective in reducing the oxidative reactions and the production of sulfur volatiles in irradiated pork by scavenging free radicals produced by irradiation (Nam and Ahn 2003). Ascorbic acid is a reducing agent, which prevented color changes in irradiated and nonirradiated ground beef during storage (Giroux and others 2001; Nam and Ahn 2003a; Wheeler and others 1996; Lee and others 1999; Sanchez-Escalante and others 2001).

In addition to color changes and accelerated lipid oxidation, irradiation produces off-odor volatiles in meat. Sulfur compounds are the major volatile compounds responsible for irradiation off-odor, produced mainly by radiolysis of sulfur-containing amino acids without any relation with those volatiles of lipid oxidation (Ahn and others 1999a, 2000, 2001). Under aerobic conditions, the sulfur compounds were highly volatile and evaporated easily, however, under vacuum storage these compounds remained in meat (Ahn and others 2001). Although aerobic packaging was very effective in eliminating the Sulfur-volatiles produced by irradiation, the amounts of volatile aldehydes in irradiated ground beef significantly increased during storage unless antioxidant additives were added. Therefore, when irradiated beef is aerobically stored, the generation of lipid oxidation products is of more concern than S-volatiles (Ahn and Nam 2004).

The objective of this study was to determine the effect of ascorbic acid and selected antioxidants on the color, lipid oxidation and off-odor volatiles of beef using different methods of additive applications.

## Materials and Methods

### Sample preparation

Four blocks of beef chucks from 2 different grocery stores were bought and used for the study. One block taken from each of 2 stores was treated as a replication. Each block was trimmed of any visible fat and ground separately through a 6-mm plate at first then through a 3-mm plate. Two sets of eight treatments were prepared, one for mixing application and the other set for spraying application. The treatments were: (1) nonirradiated control, (2) nonirradiated added with 0.05% (wt/wt) L-ascorbic acid (Fisher Scientific, Fair Lawn, NJ, USA), (3) nonirradiated added with 0.01% α-tocopherol (Aldrich Chemical Co., Milwaukee, WI USA) + 0.01% sesamol (3,4-methylenedioxyphenol; Sigma St Louis, MO, USA), (4) nonirradiated added with 0.05% (wt/wt) L-ascorbic acid + 0.01% α-tocopherol + 0.01% sesamol. Treatments 5, 6, 7 and 8 were the same as 1, 2, 3, and 4, respectively, but with irradiation. For the mixing application, each additive was added to the ground meat and then mixed for 2 min in a bowl mixer (Model KSM 90; Kitchen Aid Inc., St. Joseph, MI., USA). Ground beef patties (approximately 30 g) were made by hand, placed individually on Styrofoam trays and wrapped with clear stretch, oxygen-permeable meat film RMF-61 Hy (Borden Division, Borden Packaging and Industrial Products Inc., North Andover, MA, USA.), using a single-roll overwrapper, Model 600A (Heat Sealing Equipment Manufacturing Co., Cleveland, OH, USA). For the spraying application, ground beef patties were prepared as mentioned above then placed on trays were they sprayed from both sides with the additive solutions using an electrostatic spraying device (Electrostatic Spraying System, Inc. Watkinsville, GA, USA). After spraying, beef patties were placed on Styrofoam trays and wrapped, similar to those for mixing application, with oxygen permeable meat film. Prepared patties were stored overnight at 4Honorarium Request Form, and irradiated the next morning. The additive treatments were applied as solution form: ascorbic acid and sesamol were dissolved in distilled water, while tocopherol was dissolved first in corn oil, and then oil emulsion was prepared using the aqueous solutions of ascorbic acid and sesamol. The same amounts of water and corn oil were added to all other treatments.

**Ionizing radiation**

Wrapped beef patties were irradiated at 2.5 kGy using a linear accelerator facility (Circe IIIR; Thomson CSF Linac, St. Aubin, France) with 10 MeV of energy and 5.6 KW of power level. The average dose rate was 68.7 kGy/min. Alanine dosimeter were placed on the top and bottom surfaces of a sample and were read using a 104 Electron Paramagnetic Resonance Instrument (Bruker Instruments Inc., Billerica, Mass., USA) to check the absorbed dose. The dose range absorbed by meat samples was 2.45 to 2.95 kGy (max/min ratio was 1.20). The nonirradiated control (0 kGy) samples were exposed to ambient temperature of linear accelerator facility while others samples were irradiated. After irradiation, the irradiated and non irradiated meat samples were immediately returned to a 4° C cold room where they were displayed under fluorescent light for 7 days. Color, lipid oxidation, volatile analysis, ORP and CO production were determined at 0, 3, and 7 days of storage.

**Thiobarbituric acid-reactive substances (TBARS) measurement**

Lipid oxidation was determined using a TBARS method (Ahn and others 1999a). Five grams of ground beef were weighed into a 50-mL test tube and homogenized with 50 μL butylated hydroxytoluene (7.2%) and 15 mL of deionized distilled water (DDW) using a

Polytron homogenizer (Type PT 10/35, Brinkman Instruments Inc., Westbury NY, USA) for 15 s at high speed. One mL of the meat homogenate was transferred to a disposable test tube (13 x 100 mm), and thiobarbituric acid/trichloroacetic acid (15 mM TBA/15% TCA, 2 mL) was added. The mixture was vortex mixed and incubated in a boiling water bath for 15 min to develop color. Then samples were cooled in the ice-water for 10 min, mixed again, and centrifuged for 15 min at 2,500 x *g* at 4° C. The absorbance of the resulting supernatant solution was determined at 531 nm against a blank containing 1 mL of deionized distilled water (DDW) and 2 mL of TBA/TCA solution. The amounts of TBARS were expressed as mg of malonaldehyde (MDA) per kg of meat.

**Volatile compounds**

A purge-and-trap apparatus (Solatek 72 and Concentrator 3100; Tekmar-Dohrmann, Cincinnati, OH, USA) connected to a gas chromatograph/mass spectrometer (HP 6890/HP 5973; Hewlett-Packard Co., Wilmington, DE, USA) was used to analyze volatiles produced (Ahn and others, 2001). The ground meat sample (3 g) was placed in a 40-mL sample vial, and the vial was flushed with helium gas (40 psi) for 5 s. The maximum waiting time of a sample in a refrigerated (4° C) holding tray was less than 4 h to minimize oxidative changes before analysis (Ahn and others 2001). The meat sample was purged with helium gas (40 mL/min) for 14 min at 40° C. Volatiles were trapped using a Tenax-charcoal-silica column (Tekmar-Dohrmann) and desorbed for 2 min at 225° C, focused in a cryofocusing module (-80° C), and then thermally desorbed into a capillary column for 60 s at 225° C.

An HP-624 column (8.5 m x 0.25 mm i.d., 1.4 μm nominal), an HP-1 column (60 m x 0.25 mm i.d., 0.25 μm nominal; Hewlett-Packard), and an HP-Wax column (6.5 m x 0.25 mm i.d., 0.25 μm nominal) were connected using zero dead-volume column connectors (J &W Scientific, Folsom, CA, USA). Ramped oven temperature was used to improve volatile separation. The initial oven temperature of 30° C was held for 6 min. After that, the oven temperature was increased to 60° C at 5° C/min, increased to 180° C at 20° C/min, increased to 210° C at 15° C/min, and then was held for 5 min at the temperature. Constant column pressure at 22.5 psi was maintained. The ionization potential of the mass selective detector (Model 5973; Hewlett-Packard) was 70 eV, and the scan range was 19.1 to 400 m/z.

Identification of volatiles was achieved by comparing mass spectral data of samples with those of the Wiley Library (Hewlett-Packard). Standards were used to confirm the identification by the mass-selective detector. The area of each peak was integrated using the ChemStation (Hewlett-Packard), and the total peak area (pA*s x $10^4$) was reported as an indicator of volatiles generated from the sample.

**Color measurement**

The color of meat was measured on the surface of meat samples using a Labscan spectrophotometer (Hunter Associated Labs Inc., Reston, VA, USA) that had been calibrated against white and black reference tiles covered with the same film as those used for meat samples. CIE L*- (lightness), a*- (redness), and b*- (yellowness) values were obtained (AMSA 1991) using an illuminant A (light source). Area view and port size were 0.25 and 0.40 inch, respectively. An average value from 2 random locations on each side, upper and lower, of sample surface was used for statistical analysis.

**Oxidation-reduction potential (ORP)**

The method of Moiseeve and Cornforth (1999) were used in determining the change of ORP in meat. A pH/ion meter (Accumet 25, Fisher Scientific) connected to a platinum electrode filled with a 4 M-KCl solution saturated with AgCl was tightly inserted in the center of meat sample. To minimize the effect of air, the smallest possible pore was made before inserting the electrode and recording the ORP readings (mV).

**Carbon monoxide (CO)**

To measure carbon monoxide produced by irradiation, carbon monoxide (CO) gas was purchased from Aldrich (Milwaukee, WI, USA). The standard gas was analyzed using a gas chromatograph (GC, Model 6890; Hewlett Packard Co., Wilmington, DE, USA) with a flame ionization detector (FID). The method of Furuta and others (1992) was modified for the detection of carbon-related gases. Meat sample (10g) was placed in a 24-mL glass vial, and the vials were flushed with helium gas (40 psi) for 5 s to minimize experimental errors due to air incorporation, then samples were microwaved for 10 s at full power. Ten minutes after microwave heating, the headspace gas of each sample (200 μL) was withdrawn using an airtight syringe and injected into a splitless inlet of a GC (Model 6890; Hewlett Packard Co.). A Carboxen-1006 Plot column (30 m x 0.32 mm id; Supelco, Bellefonte, PA, USA) was used. Helium was used as a carrier gas at a constant flow of 1.8 mL/min and oven conditions were set at 120° C. A flame ionization detector (FID) equipped with a Nickel catalyst (Hewlett Packard Co.) was used for the methanization of CO and $CO_2$, and the temperatures of inlet, detector, and Nickel catalyst were 250, 280, and 375° C, respectively. Detector (FID) air, $H_2$, and make-up gas (He) flows were 350, 35, and 40 mL/min, respectively. The identification of carbon monoxide was achieved using standard gas and a GC/MS, and the area of each peak was integrated by using Chemstation software (Hewlett Packard Co.). To quantify the amount of gas released, peak areas (pA*sec) were converted to the concentration (ppm) of gas in the sample headspace (14 mL) using $CO_2$ concentration (330 ppm) in air.

**Statistical analysis**

The experiment was a complete randomized design with four replications. Data were analyzed by the procedures of generalized linear model of SAS (SAS Institute 1995). Student-Newman-Keuls' multiple-rage test was used to compare the mean values of treatments. Mean values and standard error of the means (SEM) were reported. Significance was defined at $P < 0.05$. Analysis of variance (ANOVA) was used to determine the effects of application methods, irradiation, additives and storage period on lipid oxidation, color, carbon monoxide production and oxidation-reduction potential of ground beef.

## Results and Discussion

**Lipid oxidation**

Lipid oxidation was measured and TBARS values are presented in Table 1. Application method, irradiation, additives and storage influenced the TBARS values as shown in table 1. In control samples, irradiation did not have any significant effect on lipid oxidation at 0 d of storage, regardless of the application method. Irradiated beef patties treated with ascorbic acid had higher TBARS values than nonirradiated patties treated with ascorbic acid, indicating interaction between irradiation and additives. All three additive treatments were effective in slowing down lipid oxidation where they have lower TBARS numbers compared by nonirradiated controls. This result disagree with Higgins and others (1998) who reported that direct addition of α-tocopherol had no significant effect on the inhibition of lipid oxidation in cooked turkey meat. The effect of the three treatments in lowering TBARS values were more distinct in irradiated beef compared with nonirradiated controls. As storage period increased, the TBARS values increased both in irradiated and nonirradiated beef regardless of application methods. Treatments α-tocopherol + sesamol, and ascorbic acid + α-tocopherol + sesamol were more effective in lowering TBARS values compared with ascorbic acid treatment. This difference became even larger at 7d of storage, and the treatment α-tocopherol + sesamol had the lowest TBARS values compared with the other two treatments. Two antioxidant combinations, sesamol + α-tocopherol and gallate + α-tocopherol, were effective in preventing lipid oxidation during storage (Nam and Ahn 2003b). The addition of ascorbic acid to ground meat in combination with such antioxidants as rosemary or α-tocopherol, exerted a synergistic effect (Mitsumoto and others 1991; Sanchez-Escalante and others 2001). The effectiveness of ascorbic acid in lowering TBARS values decreased as storage period increased. For the other two treatments that was not the case, where their effects as antioxidant did not decreased much at 7 day. Liu and others (1994) found that the antioxidant effect of α-tocopherol in cooked meat was less than that in raw meat. Pearson and others (1977) explained that this difference in α-tocopherol effect could be due to protein denaturation, release of heme and none heme iron, and consequently catalysis of the oxidation of unsaturated fatty acids during cooking

**Color values**

Irradiation decreased the lightness (L* value) of ground beef regardless of the application method (Table 2). Similar results were reported by Zhu and others (2003) who found significant decrease in lightness values in irradiated turkey ham. Application methods influenced the lightness of beef at 0 d, but changes were not that big. There were no differences between the upper and lower surfaces of beef patties. None of the treatments affected L* value. Lightness of beef also didn't change much over the storage period of 7d. Houser and others (2003) found that storage had no significant effects on L* for irradiated cured ham. Also, Nam and Ahn (2002a) reported that packaging, irradiation and storage did not have any effect of L* value for precooked turkey breast.

Irradiation, additive treatments and storage influenced the redness (a* value) of beef (Table 3). Irradiation decreased the redness of beef for both mixing and spraying application. Luchsinger and others (1997) reported that at 2.0 kGy beef patties were less red compared with nonirradiated controls. No differences were noticed between the upper and lower surfaces of beef patties. Ascorbic acid treatment was the most effective treatment in maintaining the red color after irradiation. In nonirradiated beef, ascorbic acid increased the redness of beef. As storage increased, a* values started to decrease. At 3d, ascorbic acid was still the most effective treatment in maintaining the red color followed by: ascorbic acid + α-tocopherol +sesamol. Beef redness decreased even more with increasing storage period to 7d. The yellowness (b* values) of beef, also, was decreased by irradiation in both application methods (Table 4). Nanke and others (1999) reported that the yellowness values decreased in beef and pork because of irradiation. Ascorbic acid increased the yellowness of nonirradiated meat. As storage period increased the yellowness decreased.

**Oxidation-reduction potential (ORP)**

For both mixing and spraying application irradiation lowered the ORP values at 0d (Table 5). The reduction by irradiation in the mixing application was higher (lower ORP values) than spraying application. Lowered ORP in irradiated meat was rapidly increased under aerobic storage (Hannah and Simic 1985; Nam and Ahn 2002b). Ascorbic acid lowered ORP values in nonirradiated beef in both mixing and spraying application but the values were lower in the mixing than in the spray application. The other two treatments had a higher ORP values compared to ascorbic acid in both mixing and spraying application with spraying being higher than mixing. As storage period increased after irradiation, ORP values increased in all treatment, but ascorbic was still keeping a lower ORP compared to the others. Generally, beef with spraying application had higher values compared to the mixing application.

**Carbon monoxide (CO) production**

Irradiation increased CO production from ground beef treated with mixing or spraying application (Table 6). Amount of produced CO was higher in case of mixing than in the spraying application. Carbon monoxide was produced by radiolysis of organic components in irradiated frozen meat (Furuta and others; Woods and Pikaev 1994). None of the treatments seem to have any effect on CO production. As storage period increased, the production of CO decreased in all beef regardless of application method or additives treatments.

**Volatiles production**

Irradiation, antioxidants, and application method influenced volatile production at 0d (Tables 7 and 8). Irradiation increased total volatiles production from beef. Patties spayed with additives produced more volatiles than those mixed with additives. Hydrocarbons and alcohols produced from beef sprayed with additive were higher than those produced from beef mixed with additives. Hydrocarbon and sulfur compounds and 1-butene, toluene, dimethyl sulfide, and dimethyl disulfide were distinctly produced from cooked turkey breast (Nam and Ahn 2003b).The addition of ascorbic acid, α-tocopherol + sesamol, and ascorbic acid + α-tocopherol + sesamol lowered the produced alcohols and aldehydes from both application methods. There was no big difference between the effects of the three treatments. At 3d of storage (Tables 9 and 10) total volatiles produced by irradiation decreased in both application methods. Alcohols produced by spraying application where higher than that produced by mixing application. Treatments α-tocopherol + sesamol, and ascorbic acid + α-tocopherol + sesamol were more effective in lowering the produced aldehydes in irradiated beef compared with the ascorbic acid treatment. Nam and others (2006) reported that the combination of rosemary-tocopherol reduced the amount of hexanal in pork loin to 30% of the irradiated control. Hexanal is a common indicator of lipid oxidation in meat (Ahn and others 1999b). As storage period increased to 7d (Tables 11 and 12) total volatiles in nonirradiated meat increased drastically in both application methods. Alcohols were the highest contributor to that increase. Treatment ascorbic acid + α-tocopherol + sesamol were the more effective treatment in lowering the produced aldehydes and alcohols in both application methods.

## Conclusions

Beef patties treated with spraying produced more volatiles, hydrocarbons and alcohols; and had higher ORP values compared with those treated with mixing. This indicated that patties, to which antioxidants were applied on the surfaces, would be more susceptible to oxidative changes compared to those in which antioxidants were mixed. Therefore, using mixing method for applying of ascorbic acid and antioxidants is recommended to avoid any quality changes in irradiated ground beef.

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Table 1. TBARS values of beef mixed or sprayed with different additives

(Unit: mg MDA/kg meat)

| | Mixing | | | Spraying | | |
|---|---|---|---|---|---|---|
| | NIR | IR | SEM | NIR | IR | SEM |
| ***Day 0*** | | | | | | |
| Cont. | 0.87 | 0.91$^{a}$ | 0.26 | 0.97$^{a}$ | 0.75$^{a}$ | 0.16 |
| A | 0.33$^{y}$ | 0.50$^{bx}$ | 0.03 | 0.53$^{by}$ | 0.83$^{ax}$ | 0.06 |
| E+S | 0.29 | 0.34$^{b}$ | 0.03 | 0.42$^{b}$ | 0.47$^{b}$ | 0.05 |
| A+E+S | 0.30 | 0.35$^{b}$ | 0.03 | 0.47$^{b}$ | 0.55$^{b}$ | 0.04 |
| SEM | 0.14 | 0.12 | | 0.12 | 0.05 | |
| ***Day 3*** | | | | | | |
| Cont. | 1.27$^{a}$ | 2.00$^{a}$ | 0.38 | 0.89$^{ay}$ | 1.94$^{ax}$ | 0.25 |
| A | 0.45$^{by}$ | 1.06$^{bx}$ | 0.11 | 0.76$^{aby}$ | 2.29$^{ax}$ | 0.17 |
| E+S | 0.26$^{b}$ | 0.30$^{c}$ | 0.03 | 0.37$^{b}$ | 0.45$^{b}$ | 0.04 |
| A+E+S | 0.31$^{b}$ | 0.33$^{c}$ | 0.03 | 0.37$^{b}$ | 0.46$^{b}$ | 0.03 |
| SEM | 0.20 | 0.20 | | 0.11 | 0.19 | |
| ***Day 7*** | | | | | | |
| Cont. | 1.55 | 3.06$^{a}$ | 0.66 | 1.06$^{ay}$ | 3.01$^{ax}$ | 0.31 |
| A | 0.51$^{y}$ | 1.68$^{bx}$ | 0.15 | 0.85$^{aby}$ | 3.85$^{ax}$ | 0.43 |
| E+S | 0.31 | 0.36$^{b}$ | 0.03 | 0.42$^{b}$ | 0.45$^{b}$ | 0.05 |
| A+E+S | 0.3$^{z}$ | 0.36$^{b}$ | 0.03 | 0.46$^{b}$ | 0.51$^{b}$ | 0.04 |
| SEM | 0.30 | 0.37 | | 0.14 | 0.35 | |

| | DF | F value | Pr |
|---|---|---|---|
| Application (A) | 1 | 11.88 | 0.0007 |
| Irradiation (IR) | 1 | 71.35 | 0.0001 |
| Additives (AD) | 3 | 85.12 | 0.0001 |
| Storage (S) | 2 | 33.26 | 0.0001 |
| A x IR | 1 | 5.58 | 0.0195 |
| A x AD | 3 | 10.19 | 0.0001 |
| A x S | 2 | 0.71 | 0.4948 |
| IR x AD | 3 | 19.94 | 0.0001 |
| IR x S | 2 | 18.31 | 0.0001 |
| AD x S | 6 | 11.32 | 0.0001 |
| A x IR x AD | 3 | 3.37 | 0.0203 |
| A x IR x S | 2 | 1.92 | 0.1510 |
| A x AD x S | 6 | 1.70 | 0.1242 |
| IR x AD x S | 6 | 6.28 | 0.0001 |
| A x IR x AD x S | 6 | 0.94 | 0.4698 |

$^{a-c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)

$^{x-y}$ Values with different letters within a row of each application are significantly different ($P$<0.05)

*Abbreviation:* NIR; non-irradiated samples, IR; irradiated samples, Cont.; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 2. CIE color L*-values of beef mixed or sprayed with different additives

| | Mixing | | | | | Spraying | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | | IR | | | Non-IR | | IR | | |
| | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM |
| ***Day 0*** | | | | | | | | | | |
| Cont. | 46.00$^{w}$ | 44.93$^{abw}$ | 42.67$^{x}$ | 41.02$^{y}$ | 0.45 | 45.25$^{w}$ | 44.62$^{w}$ | 41.90$^{x}$ | 38.86$^{y}$ | 0.41 |
| A | 45.87$^{w}$ | 45.75$^{aw}$ | 41.87$^{x}$ | 41.05$^{x}$ | 0.51 | 45.59$^{w}$ | 44.61$^{w}$ | 40.48$^{x}$ | 40.26$^{x}$ | 0.57 |
| E +S | 44.81$^{w}$ | 43.5$^{bx}$ | 40.95$^{y}$ | 40.82$^{y}$ | 0.43 | 45.35$^{w}$ | 44.62$^{w}$ | 40.35$^{x}$ | 39.66$^{x}$ | 0.54 |
| A+E+S | 45.3$^{w}$ | 44.64$^{abw}$ | 42.09$^{x}$ | 41.28$^{x}$ | 0.55 | 45.79$^{w}$ | 44.81$^{w}$ | 40.60$^{x}$ | 41.67$^{x}$ | 0.64 |
| SEM | 0.47 | 0.42 | 0.49 | 0.56 | | 0.38 | 0.52 | 0.45 | 0.76 | |
| ***Day 3*** | | | | | | | | | | |
| Cont. | 45.49$^{bc}$ | 44.63 | 45.23 | 43.85 | 0.51 | 43.33$^{b}$ | 42.84 | 42.09 | 42.00 | 0.56 |
| A | 47.46$^{aw}$ | 46.34w | 45.35$^{wx}$ | 43.84$^{x}$ | 0.62 | 45.9$^{aw}$ | 44.8$^{w}$ | 43.44$^{x}$ | 41.23$^{y}$ | 0.45 |
| E+S | 44.48$^{c}$ | 44.60 | 43.56 | 43.09 | 0.70 | 43.34b | 43.01 | 42.56 | 41.83 | 0.55 |
| A+E+S | 46.31$^{abw}$ | 44.75$^{w}$ | 44.91$^{w}$ | 43.21$^{x}$ | 0.47 | 44.71$^{abw}$ | 44.16$^{wx}$ | 43.00$^{wx}$ | 42.47$^{x}$ | 0.53 |
| SEM | 0.49 | 0.68 | 0.60 | 0.52 | | 0.46 | 0.58 | 0.50 | 0.55 | |
| ***Day 7*** | | | | | | | | | | |
| Cont. | 46.07$^{cwx}$ | 45.47$^{abwx}$ | 46.95$^{aw}$ | 44.66$^{x}$ | 0.58 | 43.80$^{wx}$ | 42.92$^{abx}$ | 44.29$^{w}$ | 42.56$^{x}$ | 0.39 |
| A | 45.80$^{a}$ | 45.97$^{a}$ | 46.15$^{a}$ | 45.32 | 0.63 | 43.14 | 44.37$^{a}$ | 43.48 | 43.57 | 0.60 |
| E+S | 44.71$^{c}$ | 44.08$^{b}$ | 43.93$^{b}$ | 43.61 | 0.53 | 41.56 | 41.94$^{b}$ | 42.36 | 42.33 | 0.55 |
| A+E+S | 44.11$^{b}$ | 43.89$^{b}$ | 43.40$^{b}$ | 43.01 | 0.57 | 41.81 | 42.86$^{ab}$ | 42.47 | 42.95 | 0.75 |
| SEM | 0.66 | 0.47 | 0.56 | 0.61 | | 0.64 | 0.51 | 0.55 | 0.48 | |

| | DF | F value | P | | DF | F value | P |
|---|---|---|---|---|---|---|---|
| Application (A) | 1 | 109.83 | 0.0001 | IR x S | 2 | 66.66 | 0.0001 |
| Irradiation (IR) | 1 | 159.53 | 0.0001 | AD x S | 6 | 7.38 | 0.0001 |
| Additives (AD) | 3 | 5.56 | 0.0010 | A x IR x AD | 3 | 0.15 | 0.9321 |
| Storage (S) | 2 | 26.64 | 0.0001 | A x IR x S | 2 | 1.08 | 0.3400 |
| A x IR | 1 | 2.76 | 0.0974 | A x AD x S | 6 | 0.81 | 0.5623 |
| A x AD | 3 | 1.23 | 0.2988 | IR x AD x S | 6 | 0.48 | 0.8251 |
| A x S | 2 | 12.62 | 0.0001 | A x IR x AD x S | 6 | 0.40 | 0.8779 |
| IR x AD | 3 | 4.02 | 0.0078 | | | | |

$^{a-c}$ Values with different letters within a column of each storage period are significantly different (*P*<0.05)
$^{w-y}$ Values with different letters within a row of each application are significantly different (*P*<0.05)
*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 3. CIE color a*-values of beef mixed or sprayed with different additives

| | Mixing | | | | | Spraying | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | | IR | | | Non-IR | | IR | | |
| | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM |
| ***Day 0*** | | | | | | | | | | |
| Cont. | 27.23$^{cw}$ | 26.49$^{cw}$ | 15.87$^{cx}$ | 16.97$^{bx}$ | 0.53 | 30.58$^{aw}$ | 30.18$^{abw}$ | 15.72$^{cy}$ | 16.95$^{x}$ | 0.33 |
| A | 30.43$^{aw}$ | 29.3$^{ax}$ | 17.23$^{by}$ | 16.70$^{by}$ | 0.22 | 30.27$^{aw}$ | 30.79$^{aw}$ | 16.91$^{bx}$ | 16.3$^{x}$ | 0.49 |
| E+S | 26.90$^{cw}$ | 26.08$^{cw}$ | 16.95$^{bx}$ | 17.12$^{bx}$ | 0.32 | 28.55$^{bw}$ | 29.02$^{bcw}$ | 16.91$^{bx}$ | 17.14$^{x}$ | 0.36 |
| A+E+S | 28.57$^{bw}$ | 28.02$^{bw}$ | 18.90$^{ax}$ | 18.61$^{ax}$ | 0.35 | 28.96$^{bw}$ | 28.75$^{cw}$ | 18.26$^{ax}$ | 17.57$^{x}$ | 0.24 |
| SEM | 0.45 | 0.39 | 0.26 | 0.37 | | 0.33 | 0.41 | 0.31 | 0.41 | |
| ***Day 3*** | | | | | | | | | | |
| Cont. | 21.66$^{cw}$ | 20.51$^{cw}$ | 16.05$^{cx}$ | 16.06$^{cx}$ | 0.59 | 24.73$^{cw}$ | 25.27$^{cw}$ | 17.00$^{bx}$ | 16.80$^{bx}$ | 0.32 |
| A | 30.55$^{aw}$ | 29.53$^{aw}$ | 22.94$^{ax}$ | 22.36$^{ax}$ | 0.45 | 30.24$^{aw}$ | 30.61$^{aw}$ | 21.77$^{ax}$ | 21.77$^{ax}$ | 0.46 |
| E+S | 19.60$^{dw}$ | 18.86$^{dx}$ | 16.37$^{cy}$ | 16.29$^{cy}$ | 0.22 | 22.60$^{dw}$ | 23.35$^{dw}$ | 17.37$^{bx}$ | 17.19$^{bx}$ | 0.40 |
| A+E+S | 25.32$^{bw}$ | 25.16$^{bw}$ | 21.24$^{bx}$ | 21.12$^{bx}$ | 0.33 | 26.76$^{bw}$ | 27.16$^{bw}$ | 21.32$^{ax}$ | 20.91$^{ax}$ | 0.40 |
| SEM | 0.41 | 0.52 | 0.31 | 0.43 | | 0.41 | 0.51 | 0.27 | 0.37 | |
| ***Day 7*** | | | | | | | | | | |
| Cont. | 13.71$^{c}$ | 13.59$^{b}$ | 14.39$^{b}$ | 15.83$^{c}$ | 0.75 | 16.21$^{cwx}$ | 16.93$^{cw}$ | 13.85$^{bx}$ | 15.58$^{cwx}$ | 0.68 |
| A | 21.76$^{a}$ | 19.87$^{a}$ | 22.89$^{a}$ | 22.99$^{a}$ | 0.97 | 22.92$^{aw}$ | 22.64$^{aw}$ | 16.60$^{ay}$ | 19.50$^{ax}$ | 0.73 |
| E+S | 13.01$^{cx}$ | 14.41$^{bwx}$ | 13.85$^{cx}$ | 15.55$^{cw}$ | 0.43 | 13.51$^{dy}$ | 15.04$^{cx}$ | 16.19$^{awx}$ | 17.12$^{bw}$ | 0.50 |
| A+E+S | 17.03$^{bx}$ | 17.75$^{awx}$ | 19.53$^{bw}$ | 19.80$^{bw}$ | 0.59 | 18.15$^{bx}$ | 19.25$^{buwx}$ | 17.16$^{ax}$ | 20.36$^{aw}$ | 0.61 |
| SEM | 0.73 | 1.00 | 0.57 | 0.39 | | 0.59 | 0.74 | 0.67 | 0.50 | |

| | DF | F value | P | | DF | F value | P |
|---|---|---|---|---|---|---|---|
| Application (A) | 1 | 9.22 | 0.0026 | IR x S | 2 | 426.54 | 0.0001 |
| Irradiation (IR) | 1 | 1582.86 | 0.0001 | AD x S | 6 | 114.66 | 0.0001 |
| Additives (AD) | 3 | 118.26 | 0.0001 | A x IR x AD | 3 | 2.11 | 0.0987 |
| Storage (S) | 2 | 389.31 | 0.0001 | A x IR x S | 2 | 14.11 | 0.0001 |
| A x IR | 1 | 78.81 | 0.0001 | A x AD x S | 6 | 7.43 | 0.0001 |
| A x AD | 3 | 5.18 | 0.0016 | IR x AD x S | 6 | 8.27 | 0.0001 |
| A x S | 2 | 4.28 | 0.0146 | A x IR x AD x S | 6 | 1.89 | 0.0823 |
| IR x AD | 3 | 9.04 | 0.0001 | | | | |

$^{a\text{-}c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)

$^{w\text{-}y}$ Values with different letters within a row of each application are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 4. CIE color b*-values of beef mixed or sprayed with different additives

| | Mixing | | | | | Spraying | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | | IR | | | Non-IR | | IR | | |
| | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM |
| ***Day 0*** | | | | | | | | | | |
| Cont. | 23.70$^{bw}$ | 23.70$^{bw}$ | 15.36$^{cy}$ | 17.34$^{x}$ | 0.50 | 25.44$^{w}$ | 26.35$^{aw}$ | 15.46$^{cy}$ | 17.83$^{x}$ | 0.36 |
| A | 26.20$^{aw}$ | 25.30$^{ax}$ | 17.30$^{by}$ | 17.38$^{y}$ | 0.28 | 25.19$^{w}$ | 26.44$^{aw}$ | 16.99$^{bx}$ | 17.51$^{x}$ | 0.44 |
| E+S | 24.08$^{bw}$ | 23.99$^{bw}$ | 17.65$^{abx}$ | 18.30$^{x}$ | 0.32 | 24.55$^{w}$ | 24.96$^{bw}$ | 17.88$^{abx}$ | 18.65$^{x}$ | 0.40 |
| A+E+S | 24.96$^{bw}$ | 25.10$^{aw}$ | 18.60$^{ax}$ | 18.75$^{x}$ | 0.36 | 25.04$^{w}$ | 24.94$^{bw}$ | 18.33$^{ax}$ | 17.67$^{x}$ | 0.31 |
| SEM | 0.38 | 0.32 | 0.35 | 0.42 | | 0.36 | 0.35 | 0.35 | 0.45 | |
| ***Day 3*** | | | | | | | | | | |
| Cont. | 21.07$^{cw}$ | 21.42$^{cw}$ | 17.71$^{cx}$ | 18.34$^{bx}$ | 0.37 | 22.27$^{bx}$ | 23.73$^{bw}$ | 18.34$^{by}$ | 19.15$^{by}$ | 0.35 |
| A | 26.25$^{aw}$ | 25.13$^{aw}$ | 20.81$^{ax}$ | 20.42$^{ax}$ | 0.48 | 25.21$^{aw}$ | 26.29$^{aw}$ | 20.53$^{ax}$ | 20.72$^{ax}$ | 0.55 |
| E+S | 20.00$^{c}$ | 19.90$^{d}$ | 19.00$^{b}$ | 18.90$^{a}$ | 0.40 | 20.74$^{cx}$ | 22.56$^{bw}$ | 19.28$^{aby}$ | 19.16$^{by}$ | 0.43 |
| A+E+S | 23.13$^{bw}$ | 22.93$^{bw}$ | 20.15$^{ax}$ | 20.23$^{ax}$ | 0.40 | 23.38$^{bw}$ | 24.33$^{bw}$ | 20.04$^{ax}$ | 19.85$^{abx}$ | 0.41 |
| SEM | 0.43 | 0.45 | 0.33 | 0.44 | | 0.41 | 0.58 | 0.39 | 0.38 | |
| ***Day 7*** | | | | | | | | | | |
| Cont. | 17.20$^{b}$ | 18.52 | 17.43$^{b}$ | 18.39$^{c}$ | 0.43 | 18.22$^{bwx}$ | 19.58$^{w}$ | 17.13$^{x}$ | 18.68$^{w}$ | 0.42 |
| A | 19.72$^{a}$ | 20.23 | 20.84$^{a}$ | 20.81$^{a}$ | 0.65 | 20.29$^{aw}$ | 21.04$^{w}$ | 17.50$^{x}$ | 20.00$^{w}$ | 0.45 |
| E+S | 18.26$^{abwx}$ | 19.15$^{w}$ | 17.63$^{bx}$ | 18.82$^{bcwx}$ | 0.34 | 17.26$^{by}$ | 19.54$^{w}$ | 18.23$^{x}$ | 19.08$^{wx}$ | 0.33 |
| A+E+S | 18.56$^{ab}$ | 19.95 | 19.53$^{a}$ | 19.65$^{b}$ | 0.48 | 18.44$^{bx}$ | 20.38$^{w}$ | 17.41$^{x}$ | 19.70$^{w}$ | 0.42 |
| SEM | 0.57 | 0.56 | 0.47 | 0.33 | | 0.37 | 0.43 | 0.35 | 0.46 | |

| | DF | F value | P | | DF | F value | P |
|---|---|---|---|---|---|---|---|
| Application (A) | 1 | 0.47 | 0.4920 | IR x S | 2 | 298.57 | 0.0001 |
| Irradiation (IR) | 1 | 994.56 | 0.0001 | AD x S | 6 | 20.60 | 0.0001 |
| Additives (AD) | 3 | 70.29 | 0.0001 | A x IR x AD | 3 | 2.47 | 0.0615 |
| Storage (S) | 2 | 118.71 | 0.0001 | A x IR x S | 2 | 5.12 | 0.0064 |
| A x IR | 1 | 11.29 | 0.0009 | A x AD x S | 6 | 3.25 | 0.0040 |
| A x AD | 3 | 3.31 | 0.0204 | IR x AD x S | 6 | 5.99 | 0.0001 |
| A x S | 2 | 0.53 | 0.5865 | A x IR x AD x S | 6 | 1.04 | 0.3978 |
| IR x AD | 3 | 12.99 | 0.0001 | | | | |

$^{a\text{-}c}$ Values with different letters within a column of each storage period are significantly different (*P*<0.05)

$^{w\text{-}y}$ Values with different letters within a row of each application are significantly different (*P*<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 5. ORP values of beef mixed or sprayed with different additives

(Unit: mVolt)

| | Mixing | | | Spraying | | |
|---|---|---|---|---|---|---|
| | NIR | IR | SEM | NIR | IR | SEM |
| ***Day 0*** | | | | | | |
| Cont. | $30.13^{ax}$ | $-87.75^{cy}$ | 7.01 | $56.75^{ax}$ | $2.85^{cy}$ | 8.02 |
| A | $-6.13^{b}$ | $-17.38^{b}$ | 6.11 | $30.50^{b}$ | $35.83^{b}$ | 3.06 |
| E+S | $46.19^{a}$ | $22.20^{a}$ | 9.12 | $49.73^{ay}$ | $73.63^{ax}$ | 4.70 |
| A+E+S | $7.58^{b}$ | $8.53^{a}$ | 4.12 | $12.80^{c}$ | $14.83^{c}$ | 4.96 |
| SEM | 5.62 | 7.86 | | 4.36 | 6.41 | |
| ***Day 3*** | | | | | | |
| Cont. | $69.58^{a}$ | $95.05^{a}$ | 9.66 | $113.58^{a}$ | $116.90^{a}$ | 5.43 |
| A | $27.70^{b}$ | $42.78^{b}$ | 7.00 | $72.93^{b}$ | $74.93^{b}$ | 4.97 |
| E+S | $80.15^{ay}$ | $102.23^{ax}$ | 6.10 | $117.55^{ay}$ | $120.88^{ax}$ | 0.83 |
| A+E+S | $37.53^{by}$ | $55.38^{bx}$ | 4.83 | $74.95^{b}$ | $84.45^{b}$ | 4.58 |
| SEM | 8.13 | 5.95 | | 3.25 | 5.23 | |
| ***Day 7*** | | | | | | |
| Cont. | $44.38^{a}$ | 92.33 | 16.14 | 68.38 | 113.33 | 15.80 |
| A | $-6.95^{by}$ | $88.10^{x}$ | 15.12 | $38.13^{y}$ | $98.55^{x}$ | 9.57 |
| E+S | $72.23^{ay}$ | $132.50^{x}$ | 11.35 | $46.23^{y}$ | $111.65^{x}$ | 7.74 |
| A+E+S | $55.03^{ay}$ | $90.75^{x}$ | 10.30 | $38.35^{y}$ | $93.15^{x}$ | 8.16 |
| SEM | 15.71 | 10.74 | | 10.21 | 11.39 | |

| | DF | F value | Pr |
|---|---|---|---|
| Application (A) | 1 | 94.20 | 0.0001 |
| Irradiation (IR) | 1 | 42.43 | 0.0001 |
| Additives (AD) | 3 | 52.52 | 0.0001 |
| Storage (S) | 2 | 256.99 | 0.0001 |
| A x IR | 1 | 0.81 | 0.3685 |
| A x AD | 3 | 9.78 | 0.0001 |
| A x S | 2 | 14.93 | 0.0001 |
| IR x AD | 3 | 11.24 | 0.0001 |
| IR x S | 2 | 86.85 | 0.0001 |
| AD x S | 6 | 9.17 | 0.0001 |
| A x IR x AD | 3 | 1.15 | 0.3309 |
| A x IR x S | 2 | 8.38 | 0.0004 |
| A x AD x S | 6 | 2.76 | 0.0143 |
| IR x AD x S | 6 | 8.35 | 0.0001 |
| A x IR x AD x S | 6 | 1.75 | 0.1135 |

$^{a-c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)
$^{x-y}$ Values with different letters within a row of each application are significantly different ($P$<0.05)
*Abbreviation:* NIR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 6. Carbon monoxide (CO) gas formation from beef mixed or sprayed with different additives

(Unit: ppm)

| | Mixing | | | Spraying | | |
|---|---|---|---|---|---|---|
| | NIR | IR | SEM | NIR | IR | SEM |
| ***Day 0*** | | | | | | |
| Cont. | 38.86 | 135.72 | 35.65 | $18.11^{y}$ | $83.49^{x}$ | 8.53 |
| A | $18.34^{y}$ | $85.65^{x}$ | 16.18 | $11.50^{y}$ | $91.68^{x}$ | 8.99 |
| E+S | $22.43^{y}$ | $91.70^{x}$ | 14.18 | $0.00^{y}$ | $82.01^{x}$ | 8.93 |
| A+E+S | $18.50^{y}$ | $87.33^{x}$ | 11.48 | $10.84^{y}$ | $97.23^{x}$ | 12.87 |
| SEM | 13.83 | 27.23 | | 6.05 | 12.77 | |
| ***Day 3*** | | | | | | |
| Cont. | $29.51^{ay}$ | $100.56^{ax}$ | 15.18 | $23.97^{y}$ | $74.27^{x}$ | 4.33 |
| A | $22.09^{ay}$ | $87.67^{abx}$ | 7.91 | $16.01^{aby}$ | $82.90^{ax}$ | 7.62 |
| E+S | $5.50^{by}$ | $47.85^{bx}$ | 5.01 | $5.76^{by}$ | $49.68^{bx}$ | 7.13 |
| A+E+S | $30.03^{ay}$ | $69.23^{abx}$ | 5.00 | $28.10^{ay}$ | $57.06^{abx}$ | 5.47 |
| SEM | 4.20 | 12.40 | | 4.52 | 7.64 | |
| ***Day 7*** | | | | | | |
| Cont. | $0.00^{y}$ | $85.09^{x}$ | 7.14 | $0.00^{y}$ | $49.94^{x}$ | 4.01 |
| A | $0.00^{y}$ | $61.19^{ax}$ | 7.61 | $3.60^{y}$ | $64.77^{ax}$ | 3.87 |
| E+S | $0.00^{y}$ | $27.26^{bx}$ | 2.31 | $0.00^{y}$ | $30.65^{bx}$ | 1.89 |
| A+E+S | $0.00^{y}$ | $61.04^{ax}$ | 1.71 | $0.00^{y}$ | $47.88^{abx}$ | 5.42 |
| SEM | 0.00 | 7.65 | | 1.80 | 5.36 | |

| | DF | F value | Pr |
|---|---|---|---|
| Application (A) | 1 | 6.53 | 0.0117 |
| Irradiation (IR) | 1 | 356.14 | 0.0001 |
| Additives (AD) | 3 | 8.97 | 0.0001 |
| Storage (S) | 2 | 27.94 | 0.0001 |
| A x IR | 1 | 0.64 | 0.4255 |
| A x AD | 3 | 2.56 | 0.0571 |
| A x S | 2 | 0.60 | 0.5517 |
| IR x AD | 3 | 2.29 | 0.0804 |
| IR x S | 2 | 6.82 | 0.0015 |
| AD x S | 6 | 0.88 | 0.5105 |
| A x IR x AD | 3 | 1.64 | 0.1833 |
| A x IR x S | 2 | 0.43 | 0.6511 |
| A x AD x S | 6 | 0.54 | 0.7745 |
| IR x AD x S | 6 | 0.97 | 0.4461 |
| A x IR x AD x S | 6 | 0.15 | 0.9891 |

$^{a\text{-}c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)
$^{x\text{-}y}$ Values with different letters within a row of each application are significantly different ($P$<0.05)
*Abbreviation:* NIR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 7. Volatile compounds of beef mixed with different additives after 0 day storage at 4° C

| | Cont | | A | | E+S | | A+E+S | | |
|---|---|---|---|---|---|---|---|---|---|
| Compound | NIR | IR | NIR | IR | NIR | IR | NIR | IR | SEM |
| | (Total ion counts x $10^4$) | | | | | | | | |
| ***Hydrocarbons*** | ***9847***$^{bc}$ | ***13059***$^{b}$ | ***1047***$^{d}$ | ***8661***$^{c}$ | ***24038***$^{a}$ | ***25045***$^{a}$ | ***4642***$^{cd}$ | ***9592***$^{bc}$ | ***1681*** |
| 2-Methyl-butane | 3487 | 2566 | 584 | 451 | 888 | 982 | 583 | 897 | 672 |
| 1-Pentene | 0$^{b}$ | 282$^{a}$ | 0$^{b}$ | 257$^{a}$ | 0$^{b}$ | 228$^{a}$ | 0$^{b}$ | 255$^{a}$ | 24 |
| Pentane | 4689$^{a}$ | 4473$^{a}$ | 0$^{c}$ | 2593$^{b}$ | 1596$^{bc}$ | 2339$^{b}$ | 1527$^{bc}$ | 2274$^{b}$ | 454 |
| 1-Hexene | 0$^{b}$ | 313$^{a}$ | 0$^{b}$ | 285$^{a}$ | 0$^{b}$ | 259$^{a}$ | 0$^{b}$ | 281$^{a}$ | 27 |
| Hexane | 871$^{c}$ | 1337$^{c}$ | 219$^{c}$ | 1084$^{c}$ | 21259$^{a}$ | 18026$^{b}$ | 2234$^{c}$ | 2838$^{c}$ | 995 |
| 1-Heptene | 0$^{b}$ | 445$^{a}$ | 0$^{b}$ | 373$^{a}$ | 0$^{b}$ | 334$^{a}$ | 0$^{b}$ | 342$^{a}$ | 35 |
| Heptane | 516$^{b}$ | 2110$^{a}$ | 0$^{b}$ | 1809$^{a}$ | 0$^{b}$ | 1428$^{a}$ | 0$^{b}$ | 1298$^{a}$ | 231 |
| Octane | 285$^{b}$ | 1533$^{a}$ | 244$^{b}$ | 1810$^{a}$ | 294$^{b}$ | 1448$^{a}$ | 298$^{b}$ | 1408$^{a}$ | 135 |
| | | | | | | | | | |
| ***Ketones*** | ***9027*** | ***12870*** | ***10199*** | ***14712*** | ***10102*** | ***11558*** | ***9380*** | ***14137*** | ***1597*** |
| 2-Propanone | 8715 | 8952 | 9468 | 9315 | 9858 | 8588 | 9130 | 9489 | 1564 |
| 2,3-Butanedione | 313$^{b}$ | 603$^{a}$ | 463$^{ab}$ | 520$^{ab}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 68 |
| 2-Butanone | 0$^{d}$ | 3315$^{b}$ | 269$^{d}$ | 4876$^{a}$ | 244$^{d}$ | 2971$^{c}$ | 251$^{d}$ | 4648$^{a}$ | 102 |
| | | | | | | | | | |
| ***Alcohols*** | ***6589*** | ***8601*** | ***5859*** | ***7852*** | ***4990*** | ***7283*** | ***4969*** | ***8352*** | ***1010*** |
| Ethanol | 5259 | 7081 | 5154 | 6700 | 4417 | 6443 | 4295 | 6509 | 861 |
| 1-Propanol | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 137$^{b}$ | 0$^{c}$ | 131$^{b}$ | 0$^{c}$ | 1098$^{a}$ | 27 |
| 2-Butanol | 121$^{b}$ | 341$^{a}$ | 306$^{a}$ | 320$^{a}$ | 301$^{a}$ | 362$^{a}$ | 345$^{a}$ | 352$^{a}$ | 46 |
| 1-Pentanol | 1209 | 1178 | 399 | 695 | 271 | 348 | 329 | 393 | 236 |
| | | | | | | | | | |
| ***Aldehydes*** | ***2092***$^{a}$ | ***2480***$^{a}$ | ***706***$^{b}$ | ***1246***$^{b}$ | ***952***$^{b}$ | ***1118***$^{b}$ | ***969***$^{b}$ | ***1044***$^{b}$ | ***206*** |
| Acetaldehyde | 1449$^{a}$ | 1583$^{a}$ | 532$^{b}$ | 1006$^{ab}$ | 952$^{ab}$ | 1118$^{ab}$ | 969$^{ab}$ | 1044$^{ab}$ | 150 |
| Hexanal | 643b | 897a | 174c | 240c | 0c | 0c | 0c | 0c | 81 |
| | | | | | | | | | |
| ***Cyclo compounds*** | ***0***$^{c}$ | ***383***$^{b}$ | ***0***$^{c}$ | ***666***$^{a}$ | ***0***$^{c}$ | ***608***$^{a}$ | ***0***$^{c}$ | ***626***$^{a}$ | ***23*** |
| Toluene | 0$^{c}$ | 383$^{b}$ | 0$^{c}$ | 666$^{a}$ | 0$^{c}$ | 608$^{a}$ | 0$^{c}$ | 626$^{a}$ | 23 |
| | | | | | | | | | |
| ***Total volatiles*** | ***27556***$^{c}$ | ***37392***$^{ab}$ | ***17811***$^{d}$ | ***33136***$^{c}$ | ***40082***$^{ab}$ | ***45612***$^{a}$ | ***19960***$^{d}$ | ***33750***$^{bc}$ | ***2485*** |

$^{a\text{-}c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* NIR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 8. Volatile compounds of beef sprayed with different additives after 0 day storage at 4° C

| | Cont | | A | | E+S | | A+E+S | | |
|---|---|---|---|---|---|---|---|---|---|
| Compound | NIR | IR | NIR | IR | NIR | IR | NIR | IR | SEM |
| | ------------------------- (Total ion counts x $10^4$) ------------------------- | | | | | | | | |
| ***Hydrocarbons*** | ***$12499^{bc}$*** | ***$17180^{a}$*** | ***$3617^{e}$*** | ***$8066^{de}$*** | ***$7248^{de}$*** | ***$14884^{ab}$*** | ***$6416^{de}$*** | ***$8933^{cd}$*** | ***1235*** |
| 2-Methyl-butane | 2927 | 2435 | 1198 | 1006 | 1436 | 2927 | 1696 | 1172 | 703 |
| 1-Pentene | $0^{c}$ | $199^{ab}$ | $0^{c}$ | $183^{b}$ | $0^{c}$ | $237^{ab}$ | $0^{c}$ | $274^{a}$ | 23 |
| Pentane | 2904 | 3103 | 1755 | 1402 | 1560 | 2328 | 2807 | 2206 | 426 |
| 1-Hexene | $0^{b}$ | $233^{a}$ | $0^{b}$ | $209^{a}$ | $0^{b}$ | $264^{a}$ | $0^{b}$ | $256^{a}$ | 31 |
| Hexane | $6389^{ab}$ | $7630^{a}$ | $495^{d}$ | $1621^{cd}$ | $4082^{bc}$ | $4225^{bc}$ | $1536^{cd}$ | $1335^{cd}$ | 844 |
| 1-Heptene | $0^{c}$ | $296^{b}$ | $0^{c}$ | $265^{b}$ | $0^{c}$ | $420^{a}$ | $0^{c}$ | $313^{b}$ | 33 |
| Heptane | $0^{c}$ | $1585^{a}$ | $0^{c}$ | $1688^{a}$ | $0^{c}$ | $2020^{a}$ | $0^{c}$ | $1501^{a}$ | 181 |
| Octane | $279^{c}$ | $1380^{b}$ | $170^{c}$ | $1423^{b}$ | $170^{c}$ | $2045^{a}$ | $376^{c}$ | $1527^{b}$ | 154 |
| Nonane | $0^{c}$ | $320^{ab}$ | $0^{c}$ | $269^{b}$ | $0^{c}$ | $418^{a}$ | $0^{c}$ | $350^{ab}$ | 32 |
| | | | | | | | | | |
| ***Ketones*** | ***10603*** | ***11553*** | ***9389*** | ***13762*** | ***10518*** | ***11681*** | ***10044*** | ***12564*** | ***1737*** |
| 2-Propanone | 8831 | 7239 | 8481 | 8642 | 8905 | 7482 | 8778 | 8429 | 1699 |
| 2,3-Butanedione | $1492^{b}$ | $1965^{a}$ | $633^{c}$ | $1317^{b}$ | $0^{d}$ | $0^{d}$ | $0^{d}$ | $0^{d}$ | 143 |
| 2-Butanone | $281^{d}$ | $2349^{b}$ | $274^{d}$ | $3571^{a}$ | $1463^{c}$ | $3995^{a}$ | $1133^{c}$ | $3947^{a}$ | 223 |
| 2-Pentanone | $0^{d}$ | $0^{d}$ | $0^{d}$ | $232^{a}$ | $150^{c}$ | $204^{b}$ | $134^{c}$ | $188^{b}$ | 8 |
| | | | | | | | | | |
| ***Alcohols*** | ***$12843^{ab}$*** | ***$13912^{a}$*** | ***$11521^{ab}$*** | ***$14107^{a}$*** | ***$10919^{ab}$*** | ***$11703^{ab}$*** | ***$9572^{b}$*** | ***$10740^{ab}$*** | ***815*** |
| Ethanol | 10289 | 11058 | 9147 | 11022 | 8985 | 9415 | 8182 | 9484 | 763 |
| 2-Propanol | $460^{bc}$ | $702^{ab}$ | $700^{ab}$ | $742^{ab}$ | $801^{a}$ | $963^{a}$ | $262^{c}$ | $181^{c}$ | 82 |
| 1-Propanol | 132 | 166 | 129 | 160 | 120 | 153 | 132 | 147 | 10 |
| 2-Butanol | 589 | 697 | 713 | 508 | 553 | 538 | 547 | 472 | 85 |
| 1-Butanol | $207^{ab}$ | $240^{ab}$ | $0^{c}$ | $266^{a}$ | $168^{b}$ | $212^{ab}$ | $191^{ab}$ | $201^{ab}$ | 21 |
| 1-Pentanol | $1165^{ab}$ | $1048^{bc}$ | $832^{c}$ | $1408^{a}$ | $292^{d}$ | $422^{d}$ | $259^{d}$ | $255^{d}$ | 88 |
| | | | | | | | | | |
| ***Aldehydes*** | ***$1474^{ab}$*** | ***$1927^{a}$*** | ***$705^{c}$*** | ***$1454^{ab}$*** | ***$1257^{abc}$*** | ***$1822^{ab}$*** | ***$1108^{bc}$*** | ***$1688^{ab}$*** | ***172*** |
| Acetaldehyde | $1084^{ab}$ | $1437^{a}$ | $594^{b}$ | $977^{ab}$ | $721^{b}$ | $1165^{ab}$ | $739^{b}$ | $1039^{ab}$ | 126 |
| Hexanal | $391^{a}$ | $490^{a}$ | $111^{b}$ | $289^{a}$ | $411^{a}$ | $469^{a}$ | $369^{a}$ | $465^{a}$ | 60 |
| Pentenal | $0^{c}$ | $0^{c}$ | $0^{c}$ | $188^{a}$ | $126^{b}$ | $189^{a}$ | $0^{c}$ | $184^{a}$ | 13 |
| | | | | | | | | | |
| ***Cyclo compounds*** | ***$0^{c}$*** | ***$594^{ab}$*** | ***$0^{c}$*** | ***$591^{ab}$*** | ***$0^{c}$*** | ***$715^{a}$*** | ***$0^{c}$*** | ***$553^{b}$*** | ***38*** |
| Toluene | $0^{c}$ | $594^{ab}$ | $0^{c}$ | $591^{ab}$ | $0^{c}$ | $715^{a}$ | $0^{c}$ | $553^{b}$ | 38 |
| | | | | | | | | | |
| ***Total volatiles*** | ***37419abc*** | ***45166a*** | ***25231d*** | ***37980abc*** | ***29942cd*** | ***40805ab*** | ***27140cd*** | ***34479bcd*** | ***2398*** |

$^{a-d}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* NIR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 9. Volatile compounds of beef mixed with different additives after 3 day storage at 4° C

| | Cont | | A | | E+S | | A+E+S | | |
|---|---|---|---|---|---|---|---|---|---|
| Compound | NIR | IR | NIR | IR | NIR | IR | NIR | IR | SEM |
| | ------------------------- (Total ion counts x $10^4$) ------------------------- | | | | | | | | |
| ***Hydrocarbons*** | ***6615***$^{cd}$ | ***13914***$^{b}$ | ***1823***$^{d}$ | ***10441***$^{bc}$ | ***20160***$^{a}$ | ***19542***$^{a}$ | ***4415***$^{d}$ | ***7213***$^{cd}$ | ***1435*** |
| 2-Methyl butane | 1124 | 1198 | 440 | 740 | 1291 | 812 | 926 | 943 | 252 |
| Pentane | 4140$^{ab}$ | 5247$^{a}$ | 945$^{b}$ | 2737$^{ab}$ | 872$^{b}$ | 1449$^{b}$ | 946$^{b}$ | 1254$^{b}$ | 784 |
| 1-Hexene | 0$^{b}$ | 253$^{a}$ | 0$^{b}$ | 251$^{a}$ | 0$^{b}$ | 199$^{a}$ | 0$^{b}$ | 175$^{a}$ | 26 |
| Hexane | 329$^{c}$ | 1363$^{c}$ | 0$^{c}$ | 1347$^{c}$ | 17731$^{a}$ | 13747$^{b}$ | 2221$^{c}$ | 1851$^{c}$ | 880 |
| 1-Heptene | 0$^{c}$ | 352$^{a}$ | 0$^{c}$ | 330$^{a}$ | 0$^{c}$ | 286$^{ab}$ | 0$^{c}$ | 240$^{ab}$ | 25 |
| Heptane | 280$^{c}$ | 2426$^{a}$ | 0$^{c}$ | 2247$^{a}$ | 0$^{c}$ | 1492$^{b}$ | 0$^{c}$ | 1353$^{b}$ | 142 |
| 1-Penten | 282$^{bc}$ | 592$^{a}$ | 158$^{cd}$ | 389$^{b}$ | 0$^{d}$ | 0$^{d}$ | 0$^{d}$ | 0$^{d}$ | 48 |
| Octane | 460$^{c}$ | 2179$^{a}$ | 280$^{c}$ | 2102$^{a}$ | 266$^{c}$ | 1558$^{b}$ | 321$^{c}$ | 1398$^{b}$ | 106 |
| Nonane | 0$^{b}$ | 304$^{a}$ | 0$^{b}$ | 299$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 13 |
| ***Ketones*** | ***5359***$^{b}$ | ***7407***$^{ab}$ | ***6384***$^{ab}$ | ***8807***$^{ab}$ | ***9342***$^{a}$ | ***9603***$^{a}$ | ***6965***$^{ab}$ | ***8490***$^{ab}$ | ***835*** |
| 2-Propanone | 3875 | 4995 | 5114 | 5673 | 4342 | 4398 | 5008 | 5392 | 673 |
| 2,3-Butanedione | 902$^{c}$ | 689$^{c}$ | 833$^{c}$ | 823$^{c}$ | 4790$^{a}$ | 3907$^{b}$ | 1668$^{c}$ | 1323$^{c}$ | 253 |
| 2-Butanone | 228$^{c}$ | 1348$^{b}$ | 306$^{c}$ | 2026$^{a}$ | 211$^{c}$ | 1298$^{b}$ | 288$^{c}$ | 1775$^{ab}$ | 170 |
| 2-Pentanone | 131$^{b}$ | 153$^{a}$ | 132$^{b}$ | 161$^{a}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 4 |
| 2-Heptanone | 223$^{a}$ | 221$^{a}$ | 0$^{b}$ | 125$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 29 |
| ***Alcohols*** | ***7601***$^{abc}$ | ***8965***$^{a}$ | ***5289***$^{abc}$ | ***8123***$^{ab}$ | ***4037***$^{bc}$ | ***6578***$^{abc}$ | ***3752***$^{c}$ | ***5381***$^{abc}$ | ***941*** |
| Ethanol | 4583 | 5723 | 4011 | 5581 | 3210 | 5227 | 2853 | 4165 | 731 |
| 2-Butanol | 384 | 354 | 458 | 446 | 330 | 377 | 322 | 392 | 58 |
| 1-Propanol | 200$^{a}$ | 169$^{a}$ | 0$^{b}$ | 158$^{a}$ | 0$^{b}$ | 123$^{a}$ | 0$^{b}$ | 0$^{b}$ | 25 |
| 1-Butanol | 389 | 387 | 244 | 413 | 241 | 275 | 265 | 248 | 46 |
| 1-Pentanol | 1795$^{a}$ | 2083$^{a}$ | 576$^{b}$ | 1337$^{ab}$ | 257$^{b}$ | 330$^{b}$ | 311$^{b}$ | 335$^{b}$ | 312 |
| 1-Pentanol | 250$^{a}$ | 250$^{a}$ | 0$^{b}$ | 189$^{a}$ | 0$^{b}$ | 246$^{a}$ | 0$^{b}$ | 242$^{a}$ | 29 |
| ***Aldehydes*** | ***3325***$^{ab}$ | ***4646***$^{a}$ | ***653***$^{b}$ | ***1360***$^{b}$ | ***537***$^{b}$ | ***746***$^{b}$ | ***579***$^{b}$ | ***599***$^{b}$ | ***668*** |
| Acetaldehyde | 1968$^{a}$ | 2075$^{a}$ | 498$^{b}$ | 732$^{b}$ | 537$^{b}$ | 746$^{b}$ | 579$^{b}$ | 599$^{b}$ | 259 |
| Hexanal | 1358$^{ab}$ | 2364$^{a}$ | 155$^{b}$ | 426$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 443 |
| Heptanal | 0b | 207a | 0b | 201a | 0b | 0b | 0b | 0b | 14 |
| ***Cyclo compounds*** | ***0***$^{c}$ | ***508***$^{b}$ | ***0***$^{c}$ | ***586***$^{a}$ | ***0***$^{c}$ | ***501***$^{b}$ | ***0***$^{c}$ | ***477***$^{b}$ | ***20*** |
| Toluene | 0$^{c}$ | 508$^{b}$ | 0$^{c}$ | 586$^{a}$ | 0$^{c}$ | 501$^{b}$ | 0$^{c}$ | 477$^{b}$ | 20 |
| ***Total volatiles*** | ***22900***$^{bc}$ | ***35440***$^{a}$ | ***14149***$^{c}$ | ***29316***$^{ab}$ | ***34076***$^{a}$ | ***36970***$^{a}$ | ***15710***$^{c}$ | ***22161***$^{bc}$ | ***2763*** |

$^{a-d}$ Values with different superscripts within a row are significantly different ($P<0.05$)

*Abbreviation:* NIR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 10. Volatile compounds of beef sprayed with different additives after 3 day storage at 4° C

| Compound | Cont | | A | | E+S | | A+E+S | | SEM |
|---|---|---|---|---|---|---|---|---|---|
| | NIR | IR | NIR | IR | NIR | IR | NIR | IR | |
| | (Total ion counts x $10^{4}$) | | | | | | | | |
| ***Hydrocarbons*** | ***7721$^{b}$*** | ***14966$^{a}$*** | ***3544$^{b}$*** | ***9315$^{ab}$*** | ***6139$^{b}$*** | ***15827$^{a}$*** | ***3372$^{b}$*** | ***7211$^{b}$*** | ***1921*** |
| 2-Methyl butane | 1199 | 1856 | 1339 | 1482 | 1566 | 864 | 1943 | 939 | 534 |
| Pentane | 2474$^{ab}$ | 4293$^{ab}$ | 1432 | 2536$^{ab}$ | 748$^{b}$ | 5170$^{a}$ | 775$^{b}$ | 1651$^{b}$ | 817 |
| 1,3-Butadiene | 0$^{b}$ | 162$^{a}$ | 0$^{b}$ | 185$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 16 |
| 1-Hexene | 0$^{b}$ | 247$^{a}$ | 0$^{b}$ | 197$^{a}$ | 0$^{b}$ | 269$^{a}$ | 0$^{b}$ | 205$^{a}$ | 23 |
| Hexane | 3331$^{bc}$ | 3882$^{b}$ | 239$^{c}$ | 853$^{bc}$ | 3606$^{b}$ | 6430$^{a}$ | 452$^{c}$ | 1171$^{bc}$ | 805 |
| 1-Heptene | 0$^{b}$ | 282$^{a}$ | 0$^{b}$ | 251$^{a}$ | 0$^{b}$ | 257$^{a}$ | 0$^{b}$ | 278$^{a}$ | 25 |
| Heptane | 133$^{c}$ | 1854$^{a}$ | 0$^{c}$ | 1566$^{ab}$ | 0$^{c}$ | 1335$^{b}$ | 0$^{c}$ | 1449$^{ab}$ | 131 |
| 1-Pentene | 321 | 498 | 174 | 422 | 0 | 0 | 0 | 0 | 110 |
| Octane | 262$^{c}$ | 1649$^{a}$ | 359$^{c}$ | 1592$^{ab}$ | 219$^{c}$ | 1290$^{b}$ | 203$^{c}$ | 1316$^{b}$ | 87 |
| Nonane | 0$^{b}$ | 244$^{a}$ | 0$^{b}$ | 232$^{a}$ | 0$^{b}$ | 212$^{a}$ | 0$^{b}$ | 201$^{a}$ | 13 |
| | | | | | | | | | |
| ***Ketones*** | ***5218*** | ***7080*** | ***5517*** | ***8057*** | ***5340*** | ***6393*** | ***5312*** | ***7235*** | ***773*** |
| 2-Propanone | 3361 | 3997 | 3938 | 5043 | 3582 | 3676 | 4039 | 4735 | 702 |
| 2,3-Butanedione | 1458 | 1550 | 1222 | 1203 | 1542 | 1773 | 1023 | 1201 | 222 |
| 2-Butanone | 202$^{c}$ | 1025$^{b}$ | 248$^{c}$ | 1393$^{a}$ | 217$^{c}$ | 944$^{b}$ | 250$^{c}$ | 1300$^{ab}$ | 104 |
| 3-Hexanone | 0$^{c}$ | 294$^{a}$ | 0$^{c}$ | 217b | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 21 |
| 2-Heptanone | 197$^{a}$ | 215$^{a}$ | 109$^{b}$ | 202$^{a}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 14 |
| | | | | | | | | | |
| ***Alcohols*** | ***10123$^{bc}$*** | ***13135$^{ab}$*** | ***10263$^{bc}$*** | ***14101$^{a}$*** | ***8252$^{c}$*** | ***10264$^{bc}$*** | ***7064$^{c}$*** | ***9803$^{bc}$*** | ***829*** |
| Ethanol | 6862 | 8553 | 7016 | 8579 | 6271 | 8568 | 5232 | 7611 | 734 |
| 2-Propanol | 572 | 632 | 615 | 659 | 655 | 659 | 661 | 724 | 36 |
| 1-Propanol | 141$^{b}$ | 199$^{a}$ | 116$^{b}$ | 182$^{a}$ | 0$^{c}$ | 126$^{b}$ | 0$^{c}$ | 140$^{b}$ | 11 |
| 2-Butanol | 733 | 1071 | 787 | 863 | 1028 | 639 | 899 | 991 | 140 |
| 1-Butanol | 378$^{bc}$ | 434$^{b}$ | 350$^{bc}$ | 517$^{a}$ | 299$^{c}$ | 271$^{c}$ | 273$^{c}$ | 337$^{bc}$ | 27 |
| 1-Pentanol | 1261$^{b}$ | 1945$^{b}$ | 1379$^{b}$ | 2974$^{a}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 249 |
| 1-Hexanol | 176$^{b}$ | 301$^{a}$ | 0$^{c}$ | 327$^{a}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 14 |
| | | | | | | | | | |
| ***Aldehydes*** | ***1645$^{b}$*** | ***5575$^{a}$*** | ***1311$^{b}$*** | ***4824$^{a}$*** | ***553$^{b}$*** | ***1483$^{b}$*** | ***407$^{b}$*** | ***1493$^{b}$*** | ***621*** |
| Acetaldehyde | 977 | 2069 | 876 | 1655 | 553 | 594 | 407 | 490 | 252 |
| Propanal | 0$^{b}$ | 233$^{a}$ | 0$^{b}$ | 234$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 24 |
| Hexanal | 543$^{bc}$ | 2063$^{a}$ | 435$^{bc}$ | 1658$^{ab}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 351 |
| Heptanal | 125$^{c}$ | 209$^{b}$ | 0$^{d}$ | 286$^{a}$ | 0$^{d}$ | 0$^{d}$ | 0$^{d}$ | 0$^{d}$ | 17 |
| | | | | | | | | | |
| ***Cyclo compounds*** | ***0$^{b}$*** | ***500$^{a}$*** | ***0$^{b}$*** | ***495$^{a}$*** | ***0$^{b}$*** | ***445$^{a}$*** | ***0$^{b}$*** | ***502$^{a}$*** | ***27*** |
| Toluene | 0$^{b}$ | 500$^{a}$ | 0$^{b}$ | 495$^{a}$ | 0$^{b}$ | 445$^{a}$ | 0$^{b}$ | 502$^{a}$ | 27 |
| | | | | | | | | | |
| ***Total volatiles*** | ***24707$^{bc}$*** | ***40256$^{a}$*** | ***20634$^{c}$*** | ***35802$^{a}$*** | ***20284$^{c}$*** | ***33523$^{ab}$*** | ***16156$^{c}$*** | ***25240$^{bc}$*** | ***2615*** |

$^{a-c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* NIR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 11. Volatile compounds of beef mixed with different additives after 7 day storage at 4° C

| | Cont | | A | | E+S | | A+E+S | | |
|---|---|---|---|---|---|---|---|---|---|
| Compound | NIR | IR | NIR | IR | NIR | IR | NIR | IR | SEM |
| | -------------------------- (Total ion counts x $10^4$) -------------------------- | | | | | | | | |
| ***Hydrocarbons*** | ***7736$^{cd}$*** | ***17160$^{b}$*** | ***3717$^{d}$*** | ***10430$^{c}$*** | ***20390$^{b}$*** | ***27688$^{a}$*** | ***8318$^{cd}$*** | ***8922$^{c}$*** | ***1329*** |
| 2-Methyl butane | 629$^{c}$ | 4771$^{a}$ | 1283$^{c}$ | 1654$^{c}$ | 1739$^{c}$ | 2045$^{c}$ | 3786$^{b}$ | 1167$^{c}$ | 326 |
| Pentane | 0$^{b}$ | 6705$^{a}$ | 1638$^{b}$ | 2942$^{b}$ | 1201$^{b}$ | 1813$^{b}$ | 1596$^{b}$ | 1813$^{b}$ | 783 |
| Propane | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 601$^{a}$ | 508$^{b}$ | 0$^{c}$ | 0$^{c}$ | 16 |
| 1-Hexene | 0$^{b}$ | 233$^{a}$ | 0$^{b}$ | 240$^{a}$ | 0$^{b}$ | 222$^{a}$ | 0$^{b}$ | 214$^{a}$ | 17 |
| Hexane | 5959$^{c}$ | 1367$^{d}$ | 182$^{d}$ | 1219$^{d}$ | 16648$^{b}$ | 19558$^{a}$ | 2341$^{d}$ | 2574$^{d}$ | 853 |
| 1-Heptene | 0$^{c}$ | 338$^{a}$ | 0$^{c}$ | 267$^{b}$ | 0$^{c}$ | 291$^{ab}$ | 0$^{c}$ | 239$^{b}$ | 19 |
| Heptane | 336$^{c}$ | 2009$^{a}$ | 162$^{c}$ | 1916$^{a}$ | 0$^{c}$ | 1487$^{b}$ | 280$^{c}$ | 1325$^{b}$ | 146 |
| 1-Penten | 348$^{a}$ | 0$^{b}$ | 0$^{b}$ | 365$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 44 |
| Octane | 464$^{b}$ | 1493$^{a}$ | 452$^{b}$ | 1617$^{a}$ | 201$^{b}$ | 1534$^{a}$ | 316$^{b}$ | 1340$^{a}$ | 104 |
| Nonane | 0$^{b}$ | 243$^{a}$ | 0$^{b}$ | 209$^{a}$ | 0$^{b}$ | 231$^{a}$ | 0$^{b}$ | 250$^{a}$ | 13 |
| | | | | | | | | | |
| ***Ketones*** | ***18085*** | ***12378*** | ***13056*** | ***11727*** | ***13262*** | ***12769*** | ***12634*** | ***11763*** | ***1878*** |
| 2-Propanone | 5744 | 8516 | 5766 | 8607 | 5825 | 6164 | 7112 | 8265 | 615 |
| 2,3-Butanedione | 6325$^{a}$ | 1683$^{b}$ | 2004$^{b}$ | 728$^{b}$ | 6038$^{a}$ | 4952a | 3935$^{a}$ | 1388$^{b}$ | 623 |
| 2-Butanone | 5829 | 1856 | 5088 | 2179 | 1345 | 1515 | 1587 | 2109 | 1643 |
| 2-Heptanone | 186$^{b}$ | 323$^{a}$ | 199$^{b}$ | 213$^{b}$ | 53$^{c}$ | 138$^{b}$ | 0$^{c}$ | 0$^{c}$ | 27 |
| | | | | | | | | | |
| ***Alcohols*** | ***40494$^{a}$*** | ***10511$^{b}$*** | ***52917$^{a}$*** | ***7536$^{b}$*** | ***12671$^{b}$*** | ***4434$^{b}$*** | ***17452$^{b}$*** | ***3706$^{b}$*** | ***6854*** |
| Ethanol | 34572$^{a}$ | 5756$^{b}$ | 47673$^{a}$ | 4417$^{b}$ | 10187$^{b}$ | 3265$^{b}$ | 12827$^{b}$ | 2466$^{b}$ | 6381 |
| 2-Propanol | 1007$^{ab}$ | 469$^{d}$ | 1093$^{a}$ | 480$^{d}$ | 778$^{bc}$ | 400$^{d}$ | 686$^{cd}$ | 391$^{d}$ | 79 |
| 1-Propanol | 455 | 245 | 495 | 184 | 132 | 117 | 163 | 126 | 97 |
| 2-Methyle-1-propanol | 463$^{a}$ | 0$^{b}$ | 466$^{a}$ | 0$^{b}$ | 222$^{a}$ | 0$^{b}$ | 440$^{a}$ | 0$^{b}$ | 99 |
| 1-Butanol | 434$^{b}$ | 709$^{a}$ | 395$^{b}$ | 574$^{ab}$ | 367$^{b}$ | 399$^{b}$ | 488$^{b}$ | 431$^{b}$ | 51 |
| 3-Methyl-1-butanol | 2229$^{ab}$ | 0$^{b}$ | 2335$^{ab}$ | 0$^{b}$ | 755$^{ab}$ | 0$^{b}$ | 2551$^{a}$ | 0$^{b}$ | 528 |
| 1-Pentanol | 1336$^{b}$ | 3045$^{a}$ | 460$^{b}$ | 1645$^{b}$ | 230$^{b}$ | 254$^{b}$ | 297$^{b}$ | 291$^{b}$ | 322 |
| Hexanol | 0$^{c}$ | 287$^{a}$ | 0$^{c}$ | 236$^{b}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 10 |
| | | | | | | | | | |
| ***Aldehydes*** | ***3420$^{b}$*** | ***9138$^{a}$*** | ***3156$^{b}$*** | ***1970$^{b}$*** | ***1301$^{b}$*** | ***833$^{b}$*** | ***1632$^{b}$*** | ***559$^{b}$*** | ***1240*** |
| Acetaldehyde | 2601 | 1820 | 2785 | 1041 | 1301 | 833 | 1216 | 559 | 693 |
| Propanal | 0$^{b}$ | 684$^{a}$ | 0$^{b}$ | 176$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 103 |
| 3-Methyl-butanal | 456$^{a}$ | 0$^{b}$ | 223$^{ab}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 416$^{a}$ | 0$^{b}$ | 77 |
| Hexanal | 363$^{b}$ | 6634$^{a}$ | 149$^{b}$ | 753$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 955 |
| | | | | | | | | | |
| ***Cyclo compounds*** | ***0$^{c}$*** | ***553$^{a}$*** | ***0$^{c}$*** | ***506$^{a}$*** | ***146$^{b}$*** | ***564$^{a}$*** | ***189$^{b}$*** | ***488$^{a}$*** | ***21*** |
| Toluene | 0$^{c}$ | 553$^{a}$ | 0$^{c}$ | 506$^{a}$ | 146$^{b}$ | 564$^{a}$ | 189$^{b}$ | 488$^{a}$ | 21 |
| | | | | | | | | | |
| ***Total volatiles*** | ***69735$^{a}$*** | ***49740$^{ab}$*** | ***72846$^{a}$*** | ***32169$^{b}$*** | ***47770$^{ab}$*** | ***46288$^{ab}$*** | ***40225$^{ab}$*** | ***25439$^{b}$*** | ***8582*** |

$^{a-d}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* NIR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 12. Volatile compounds of beef sprayed with different additives after 7 day storage at 4° C

| | Cont | | A | | E+S | | A+E+S | | |
|---|---|---|---|---|---|---|---|---|---|
| Compound | NIR | IR | NIR | IR | NIR | IR | NIR | IR | SEM |
| | ------------------------- (Total ion counts x $10^4$) ------------------------- | | | | | | | | |
| ***Hydrocarbons*** | ***$10212^{ab}$*** | ***$16112^{a}$*** | ***$5046^{c}$*** | ***$13245^{a}$*** | ***$11310^{a}$*** | ***$9537^{bc}$*** | ***$3790^{c}$*** | ***$7311^{c}$*** | ***1461*** |
| 2-Methyl butane | 2683 | 1420 | 1948 | 1655 | 3262 | 942 | 1168 | 1300 | 501 |
| 1-Pentene | $0^{b}$ | $194^{b}$ | $0^{b}$ | $182^{b}$ | $633^{a}$ | $122^{b}$ | $443^{a}$ | $170^{b}$ | 65 |
| Pentane | $2741^{b}$ | $5527^{a}$ | $2108^{b}$ | $4687^{a}$ | $1096^{b}$ | $1488^{b}$ | $804^{b}$ | $1563^{b}$ | 573 |
| 1-Hexene | $0^{b}$ | $224^{a}$ | $0^{b}$ | $221^{a}$ | $0^{b}$ | $184^{a}$ | $0^{b}$ | $213^{a}$ | 15 |
| Hexane | $3999^{ab}$ | $4311^{ab}$ | $385^{c}$ | $1667^{c}$ | $6083^{a}$ | $3661^{b}$ | $921^{c}$ | $1263^{c}$ | 608 |
| 1-Heptene | $0^{b}$ | $264^{a}$ | $0^{b}$ | $284^{a}$ | $0^{b}$ | $237^{a}$ | $224^{b}$ | $205^{a}$ | 25 |
| Heptane | $195^{c}$ | $1735^{ab}$ | $144^{c}$ | $1854^{a}$ | $0^{c}$ | $1355^{ab}$ | $0^{c}$ | $1246^{b}$ | 141 |
| 1-Penten | $300^{b}$ | $676^{a}$ | $226^{bc}$ | $738^{a}$ | $0^{c}$ | $0^{c}$ | $0^{c}$ | $0^{c}$ | 68 |
| Octane | $295^{c}$ | $1512^{ab}$ | $235^{c}$ | $1688^{a}$ | $237^{c}$ | $1336^{b}$ | $230^{c}$ | $1176^{b}$ | 96 |
| Nonane | $0^{c}$ | $249^{a}$ | $0^{c}$ | $271^{a}$ | $0^{c}$ | $213^{ab}$ | $0^{c}$ | $178^{b}$ | 17 |
| ***Ketones*** | ***$13542^{a}$*** | ***$11063^{abc}$*** | ***$10193^{bc}$*** | ***$9800^{bc}$*** | ***$12689^{ab}$*** | ***$9073^{c}$*** | ***$11973^{abc}$*** | ***$9643^{bc}$*** | ***710*** |
| 2-Propanone | $5684^{ab}$ | $7407^{a}$ | $6013^{ab}$ | $7125^{ab}$ | $5394^{b}$ | $6280^{ab}$ | $6107^{ab}$ | $7316^{a}$ | 402 |
| 2,3-Butanedione | $5695^{a}$ | $1744^{cd}$ | $2512^{c}$ | $968^{d}$ | $4834^{ab}$ | $1219^{d}$ | $4187^{b}$ | $799^{d}$ | 352 |
| 2-Butanone | 1884 | 1646 | 1447 | 1445 | 2217 | 1415 | 1679 | 1528 | 263 |
| 2-Heptanone | $280^{a}$ | $266^{a}$ | $222^{ab}$ | $261^{a}$ | $244^{a}$ | $160^{b}$ | $0^{c}$ | $0^{c}$ | 23 |
| ***Alcohols*** | ***$30612^{a}$*** | ***$11136^{b}$*** | ***$23866^{ab}$*** | ***$9858^{b}$*** | ***$30657^{a}$*** | ***$7179^{b}$*** | ***$29487^{a}$*** | ***$6172^{b}$*** | ***4357*** |
| Ethanol | $25633^{a}$ | $7073^{b}$ | $19487^{ab}$ | $5275^{b}$ | $26485^{a}$ | $5828^{b}$ | $24011^{a}$ | $4660^{b}$ | 4339 |
| 2-Propanol | $981^{a}$ | $664^{b}$ | $968^{a}$ | $665^{b}$ | $974^{a}$ | $603^{b}$ | $897^{a}$ | $670^{b}$ | 55 |
| 1-Propanol | $265^{ab}$ | $216^{ab}$ | $170^{ab}$ | $202^{ab}$ | $231^{ab}$ | $126^{b}$ | $283^{a}$ | $134^{b}$ | 31 |
| 2-Methyle-1-propanol | $388^{a}$ | $0^{b}$ | $319^{a}$ | $0^{b}$ | $360^{a}$ | $0^{b}$ | $473^{a}$ | $0^{b}$ | 62 |
| 1-Butanol | $483^{b}$ | $594^{a}$ | $393^{b}$ | $636^{a}$ | $389^{b}$ | $385^{b}$ | $369^{b}$ | $426^{b}$ | 33 |
| 3-Methyl-1-butanol | $1791^{b}$ | $0^{c}$ | $1647^{b}$ | $0^{c}$ | $2003^{b}$ | $0^{c}$ | $3219^{a}$ | $0^{c}$ | 275 |
| 1-Pentanol | $894^{b}$ | $2323^{a}$ | $882^{b}$ | $2774^{a}$ | $214^{b}$ | $236^{b}$ | $236^{b}$ | $281^{b}$ | 261 |
| Hexanol | $177^{b}$ | $267^{a}$ | $0^{c}$ | $307^{a}$ | $0^{c}$ | $0^{c}$ | $0^{c}$ | $0^{c}$ | 17 |
| ***Aldehydes*** | ***$2409^{b}$*** | ***$7085^{a}$*** | ***$1396^{b}$*** | ***$9343^{a}$*** | ***$2231^{b}$*** | ***$896^{b}$*** | ***$1558^{b}$*** | ***$640^{b}$*** | ***945*** |
| Acetaldehyde | $1762^{bc}$ | $2311^{ab}$ | $1198^{cd}$ | $2769^{a}$ | $1954^{bc}$ | $896^{d}$ | $1320^{cd}$ | $640^{d}$ | 201 |
| Propanal | $0^{c}$ | $461^{b}$ | $0^{c}$ | $846^{a}$ | $0^{c}$ | $0^{c}$ | $0^{c}$ | $0^{c}$ | 65 |
| 3-Methyl-butanal | $222^{b}$ | $0^{c}$ | $198^{b}$ | $0^{c}$ | $277^{a}$ | $0^{c}$ | $0^{c}$ | $0^{c}$ | 14 |
| Hexanal | $426^{b}$ | $4083^{a}$ | $0^{b}$ | $5278^{a}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | 697 |
| Heptanal | $0^{c}$ | $230^{b}$ | $0^{c}$ | $448^{a}$ | $0^{c}$ | $0^{c}$ | $239^{b}$ | $0^{c}$ | 34 |
| ***Cyclo compounds*** | ***$0^{c}$*** | ***$512^{ab}$*** | ***$0^{c}$*** | ***$558^{a}$*** | ***$0^{c}$*** | ***$479^{b}$*** | ***$0^{c}$*** | ***$472^{b}$*** | ***17*** |
| Toluene | $0^{c}$ | $512^{ab}$ | $0^{c}$ | $558^{a}$ | $0^{c}$ | $479^{b}$ | $0^{c}$ | $472^{b}$ | 17 |
| ***Total volatiles*** | ***56776a*** | ***45909ab*** | ***40501abc*** | ***42804abc*** | ***56887a*** | ***27163c*** | ***46809ab*** | ***24238c*** | ***4981*** |

$^{a-d}$ Values with different superscripts within a row are significantly different ($P$<0.05).

*Abbreviation:* NIR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

# CHAPTER 4. EFFECTS OF ASCORBIC ACID AND ANTIOXIDANTS ON COLOR, LIPID OXIDATION AND VOLATILES OF IRRADIATED GROUND BEEF WITH DIFFERENT FAT CONTENTS

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## Abstract

The effect of ascorbic acid and selected antioxidants on quality changes of irradiated ground beef with different fat content was determined. Ground beef with 10, 15 or 20% fat were prepared, added with none, 0.05% (wt/wt) ascorbic acid + 0.01% (wt/wt) α-tocopherol, or 0.05% (wt/wt) ascorbic acid + 0.01% (wt/wt) α-tocopherol + 0.01% (wt/wt) sesamol, and irradiated at a dosage of 0 or 2.5 kGy using a Linear accelerator. The meat samples were placed on Styrofoam trays and wrapped with oxygen permeable plastic film, and displayed under fluorescent light for 14 days at 4° C. Color, lipid oxidation, volatiles, oxidation-reduction potential (ORP) and carbon monoxide (CO) production were determined at 0, 3, 7 and 14 days of storage. Irradiation increased lipid oxidation of ground beef regardless of their fat contents. Adding sesamol to ascorbic acid + α-tocopherol made them more effective in reducing lipid oxidation during storage. Irradiation increased total volatiles regardless of fat contents. Hexanal was the aldehyde that increased the most by irradiation. Total aldehydes and hexanal increased drastically over the storage period. Sesamol did not increase the effectiveness of ascorbic acid + α-tocopherol in decreasing total volatiles and aldehydes any further. Lightness (L* values) decreased by irradiation, as storage period increased, however, L* values increased in all meat regardless of fat contents. Irradiation reduced the redness of ground beef but fat contents had no effect on the a-value of irradiated beef. Ascorbic acid + α-tocopherol maintained the redness of irradiated beef up to 2 weeks of storage. Sesamol lowered the redness of ground beef. Fat contents did not influence the yellowness of meat, which decreased because of irradiation. Similarly, ORP values were not affected by fat contents. Reducing power of ascorbic acid + α-tocopherol lasted for 3 days, after which ORP values increased. Without any influence from fat contents irradiation increased CO production.

Key Words: Ground beef, irradiation, fat content, antioxidants, meat quality

## Introduction

Color changes, accelerated lipid oxidation, and off-odor production are the main quality changes that happen in ground beef as a result of irradiation. Consumer decisions to purchase irradiated meat will definitely be affected by those changes. Over 700 million dollars per year could be the loss in beef at retail level in the US because of discoloration (Liu and others 1995). It was reported that 74% of consumers indicated that meat color was important in making their purchase decision where they associated bright red color with freshness (Lynch and others 1986). Color changes, caused by irradiation, are different in different meat species (Satterlee and others 1971; Luchsinger and others 1996; Ahn and others 1998). While light meat such as pork and poultry breast developed pink color when irradiated, dark meat such as beef became brown or gray color (Millar and others 1995; Nanke and others 1998; Ahn and others 1998; Kim and others 2002; Nam and Ahn 2003).

Lipid oxidation is a major cause of deterioration in the quality of meat and meat products (Asghar and others 1988; Ladikos and Lougovois 1990). The 2-thiobarbituric acid reactive substances (TBARS) test is the most commonly used method to measure lipid oxidation in meat. Rancid odor was first perceived by sensory panelists when TBA number, mg malondialdehyde/kg meat, was between 0.5 and 1.0, and this level has been serving as a guide for interpreting TBA test results (Tarladgis and others 1960). Ahn and others (1998) reported (1997) that irradiation and high fat content accelerated the lipid oxidation in raw meat during storage. Oxygen availability during storage, however, was more important than irradiation on the lipid oxidation and color values of raw patties. Irradiated meat produced more volatiles than nonirradiated patties, and the proportion of volatiles varied by the packaging-irradiation conditions of patties.

Irradiation produced characteristic off-odor in all meat species, and that odor was not related to lipid oxidation (Ahn and others 1997; 1998). Irradiation off-odor had been described by several researchers: “bloody and sweet” by Hashim and others (1995), “burned oil” or “burned feather” by Heath and others (1990), and “barbecued corn-like” odor by Ahn and others (2000b). Patterson and Stevenson (1995) reported that dimethyl trisulfide was the main off-odor compound in irradiated chicken followed by cis-3-and trans-6-nonenals, cot-1-en-3-one and bis (methylthio-) methane while others (Jo and Ahn 2000; Ahn and Lee 2002;

Fan and others 2002) reported that there are many other sulfur and non-sulfur compounds related to irradiation odor. Ahn and Lee (2002) showed that sulfur amino acids were the most susceptible to changes by irradiation. Ahn (2002) reported that sulfur compounds produced from the side chains of methionine and cysteine were the most important volatiles for off-odor production in irradiated meat. Sulfur compounds were not only produced by the radiolytic cleavage of side chains (primary reaction) of sulfur amino acids, but also by the secondary reactions of the primary sulfur compounds with other compounds around them. Among the sulfur amino acids, methionine was the major amino acid responsible for irradiation off-odor because methionine produced more than 99% of sulfur compounds by irradiation.

The objective of this study was to determine the effect of ascorbic acid and selected antioxidants on the color, lipid oxidation and off-odor volatiles of ground beef with different fat content.

## Materials and Methods

### Sample preparation

Four blocks of beef top rounds from 2 different grocery stores were bought and used for the study. One block taken from each of the 2 stores was treated as a replication. High fat beef trimmings were also bought from retail stores and used to adjust fat content of ground beef for the study. Fat percent was first measured in the high fat trimming and appropriate amount were added to beef in order to get ground beef containing 10%, 15%, and 20% fat. Each meat block was trimmed of any visible fat and ground separately through a 6-mm plate. Ground meat from each of the 4 replicates was divided into 3 portions and appropriate amount of fat were added to each portions in order to prepare ground beef with 3 different fat percentages (10, 15 and 20% fat). Each of those 3 portions of meat with the added fat was ground separately twice through 6-mm plate. Six different treatments were prepared from each of the 3 portions: (1) nonirradiated control, (2) nonirradiated meat added with 0.05% (wt/wt) L-ascorbic acid (Fisher Scientific, Fair Lawn, NJ, USA) + 0.01% α-tocopherol (Aldrich Chemical Co., Milwaukee, WI, USA), (3) nonirradiated meat added with 0.05% (wt/wt) L-ascorbic acid + 0.01% α-tocopherol + 0.01% sesamol (3,4-methylenedioxyphenol;

Sigma St Louis, MO, USA). Treatments 4, 5, and 6 were the same as 1, 2, and 3, respectively, but with 2.5 kGy irradiation. Each additive was added to the ground meat and then mixed for 2 min in a bowl mixer (Model KSM 90; Kitchen Aid Inc., St. Joseph, MI., USA). Ground beef patties (approximately 30 g) were made by hand, placed individually on Styrofoam trays and wrapped with clear stretch, oxygen-permeable meat film RMF-61 Hy (Borden Division, Borden Packaging and Industrial Products Inc., North Andover, MA, USA), using a single-roll overwrapper, Model 600A (Heat Sealing Equipment Manufacturing Co., Cleveland, OH, USA). Prepared patties were stored overnight at 4° C, and irradiated the next morning. The additive treatments were applied as solution form: ascorbic acid and sesamol were dissolved in distilled water, while tocopherol was dissolved first in corn oil, and then oil emulsion was prepared using the aqueous solutions of ascorbic acid and sesamol. The same amounts of water and corn oil were added to all other treatments.

**Ionizing radiation**

Wrapped beef patties were irradiated at 0 or 2.5 kGy using a linear accelerator facility (Circe IIIR; Thomson CSF Linac, St. Aubin, France) with 10 MeV of energy and 5.6 KW of power level. The average dose rate was 68.7 kGy/min. Alanine dosimeters were placed on the top and bottom surfaces of a sample and were read using a 104 Electron Paramagnetic Resonance Instrument (Bruker Instruments Inc., Billerica, Mass., USA) to check the absorbed dose. The dose range absorbed by meat samples was 2.45 to 2.95 kGy (max/min ration was 1.20). The nonirradiated control (0 kGy) samples were exposed to ambient temperature of linear accelerator facility while others samples were irradiated. After irradiation, the irradiated and non irradiated meat samples were immediately returned to a 4° C cold room where they displayed under fluorescent light for 14 days. Color, lipid oxidation, volatile analysis, oxidation-reduction potential (ORP) and carbon monoxide (CO) production were determined at 0, 3, 7, and 14 days of storage.

**Thiobarbituric acid-reactive substances (TBARS) measurement**

Lipid oxidation was determined using a TBARS method (Ahn and others 1999). Five grams of ground beef were weighed into a 50-mL test tube and homogenized with 50 µL butylated hydroxytoluene (7.2%) and 15 mL of deionized distilled water (DDW) using a Polytron homogenizer (Type PT 10/35, Brinkman Instruments Inc., Westbury NY, USA) for 15 s at high speed. One mL of the meat homogenate was transferred to a disposable test tube (13 x 100 mm), and thiobarbituric acid/trichloroacetic acid (15 mM TBA/15% TCA, 2 mL) was added. The mixture was vortex mixed and incubated in a boiling water bath for 15 min to develop color. Then samples were cooled in the ice-water for 10 min, mixed again, and centrifuged for 15 min at 2,500 x *g* at 4° C. The absorbance of the resulting supernatant solution was determined at 531 nm against a blank containing 1 mL of DDW and 2 mL of TBA/TCA solution. The amounts of TBARS were expressed as mg of malonaldehyde (MDA) per kg of meat.

**Color measurement**

The color of meat was measured on the surface of meat samples using a Labscan spectrophotometer (Hunter Associated Labs Inc., Reston, VA, USA) that had been calibrated against white and black reference tiles covered with the same film as those used for meat samples. CIE L*- (lightness), a*- (redness), and b*- (yellowness) values were obtained (AMSA 1991) using an illuminant A (light source). Area view and port size were 0.25 and 0.40 inch, respectively. An average value from 2 random locations on each side, upper and lower, of sample surface was used for statistical analysis.

**Oxidation-reduction potential (ORP)**

The method of Moiseeve and Cornforth (1999) were used in determining the change of ORP in meat. A pH/ion meter (Accumet 25, Fisher Scientific) connected to a platinum electrode filled with a 4 M-KCl solution saturated with AgCl was tightly inserted in the center of meat sample. To minimize the effect of air, the smallest possible pore was made before inserting the electrode and recording the ORP readings (mV).

**Carbon monoxide (CO)**

To measure carbon monoxide produced by irradiation, carbon monoxide (CO) gas was purchased from Aldrich (Milwaukee, WI, USA). The standard gas was analyzed using a gas chromatograph (GC, Model 6890; Hewlett Packard Co., Wilmington, DE, USA) with a flame ionization detector (FID). The method of Furuta and others (1992) was modified for the detection of carbon-related gases. Meat sample (10 g) was placed in a 24-mL glass vial, and the vials were flushed with helium gas (40 psi) for 5 s to minimize experimental errors due to air incorporation, then samples were microwaved for 10 s at full power. Ten minutes after microwave heating, the headspace gas of each sample (200 μL) was withdrawn using an airtight syringe and injected into a splitless inlet of a GC (Model 6890; Hewlett Packard Co.). A Carboxen-1006 Plot column (30 m x 0.32 mm id; Supelco, Bellefonte, PA, USA) was used. Helium was used as a carrier gas at a constant flow of 1.8 mL/min and oven conditions were set at 120 °C. A flame ionization detector (FID) equipped with a Nickel catalyst (Hewlett Packard Co.) was used for the methanization of CO and $CO_2$, and the temperatures of inlet, detector, and Nickel catalyst were 250, 280, and 375 °C, respectively. Detector (FID) air, $H_2$, and make-up gas (He) flows were 350, 35, and 40 mL/min, respectively. The identification of carbon monoxide was achieved using standard gas and a GC/MS, and the area of each peak was integrated by using Chemstation software (Hewlett Packard Co.). To quantify the amounts of gas released, peak areas (pA*sec) were converted to the concentration (ppm) of gas in the sample headspace (14 mL) using $CO_2$ concentration (330 ppm) in air.

**Volatile compounds**

A purge-and-trap apparatus (Solatek 72 and Concentrator 3100; Tekmar-Dohrmann, Cincinnati, OH, USA) connected to a gas chromatograph/mass spectrometer (HP 6890/HP 5973; Hewlett-Packard Co., Wilmington, DE, USA) was used to analyze volatiles produced (Ahn and others 2001). The ground meat sample (3 g) was placed in a 40-mL sample vial, and the vial was flushed with helium gas (40 psi) for 5 s. The maximum waiting time of a sample in a refrigerated (4° C) holding tray was less than 4 h to minimize oxidative changes before analysis (Ahn and others 2001). The meat sample was purged with helium gas (40 mL/min) for 14 min at 40° C. Volatiles were trapped using a Tenax-charcoal-silica column (Tekmar-Dohrmann) and desorbed for 2 min at 225° C, focused in a cryofocusing module (-80° C), and then thermally desorbed into a capillary column for 60 s at 225° C.

An HP-624 column (8.5 m x 0.25 mm i.d., 1.4 μm nominal), an HP-1 column (60 m x 0.25 mm i.d., 0.25 μm nominal; Hewlett-Packard), and an HP-Wax column (6.5 m x 0.25 mm i.d., 0.25 μm nominal) were connected using zero dead-volume column connectors (J &W Scientific, Folsom, CA, USA). Ramped oven temperature was used to improve volatile separation. The initial oven temperature of 30° C was held for 6 min. After that, the oven temperature was increased to 60° C at 5° C/min, increased to 180° C at 20° C/min, increased to 210° C at 15° C/min, and then was held for 5 min at the temperature. Constant column pressure at 22.5 psi was maintained. The ionization potential of the mass selective detector (Model 5973; Hewlett-Packard) was 70 eV, and the scan range was 19.1 to 400 m/z. Identification of volatiles was achieved by comparing mass spectral data of samples with those of the Wiley Library (Hewlett-Packard). Standards were used to confirm the identification by the mass-selective detector. The area of each peak was integrated using the ChemStation (Hewlett-Packard), and the total peak area (pA*s x $10^4$) was reported as an indicator of volatiles generated from the sample.

### Statistical analysis

The experiment was a complete randomized design with four replications. Data were analyzed by the procedures of generalized linear model of SAS (SAS Institute 1995). Student-Newman-Keuls' multiple-range test was used to compare the mean values of treatments. Mean values and standard error of the means (SEM) were reported. Significance was defined at $P < 0.05$. Analysis of variance (ANOVA) was used to determine the effects of fat content, irradiation, additives and storage period on lipid oxidation, color, carbon monoxide production and oxidation-reduction potential of ground beef.

## Results and Discussion

### Lipid oxidation

Lipid oxidation was measured and TBARS values are presented in Table 1. TBARS values for most of the beef patties were not significantly different from irradiated ones with few exception where irradiated patties had higher TBARS values than nonirradiated. Those exception were in patties treated with additives and patties stored for 7 and 14 days, indicating an interaction between irradiation, additives and storage times. This result disagrees with Jo and others (1999) who reported that TBARS values increased with increased fat content in cooked pork sausage. The effects of irradiation on TBARS values were not affected by fat content. Irradiation accelerated lipid oxidation in meat stored only under aerobic conditions (Katusin-Razem and others 1992; Ahn and others 2000a).Ascorbic acid + α-tocopherol was effective in reducing lipid oxidation to a lower level-in beef with different fat contents- than that of control beef patties. Buckley and others (1995) and Liu and others (1995) reported that tocopherol is a major antioxidant in the cells and protect cell membrane fatty acids and cholesterol from the damages caused by free radicals such as hydroxyl and superoxide radicals Adding sesamol to ascorbic acid + α-tocopherol made them more effective in reducing lipid oxidation especially during late storage period of 7 and 14 days. As storage time increased, overall lipid oxidation increased, and the rate of lipid oxidation was faster in irradiated than nonirradiated beef ($P < 0.05$). Jo and others (1999) found that at 0 day, irradiated meat had higher TBARS than nonirradiated ones, and as storage time increased the difference in TBARS values disappeared. The effect of antioxidants in ground beef was more distinct after 7d of storage than at 0 d. Tocopherol content in meat product depends on adding vitamin E to the diet or direct addition during product processing. Storage stability of raw meat can be improved by increasing vitamin E concentration in processed products (Ajuyah and others 1993; Winne and Dirinck 1996). Irradiation generates free radicals that can destroy the antioxidants in muscle and consequently will reduce storage stability and increase the production of off-flavor in meat (Thayer and others 1993; Lakritz and others 1995).

**Color values**

The lightness (L* values) of ground beef was affected by irradiation (Table 2). Initially at 0 d, irradiation decreased L* values of the upper surface of beef patties treated with no additives regardless of fat contents. As storage period increased, at 14 d, the lightness of irradiated controls patties increased in all fat contents compared with nonirradiated controls. Fat contents influenced the lightness of both irradiated and nonirradiated beef, where L* increased as fat contents increased through out the storage period. Adding ascorbic acid + α-tocopherol decreased the lightness of beef. However, this effect was not consistent and non significant in some cases. Patties treated with sesamol + ascorbic + α-tocopherol had lower L* values compared to those without sesamol. Lightness of beef did not show any difference between the upper and lower surface of patties.

Irradiation reduced the redness (a* values) of ground beef at 0 day of storage (Table 3), as storage period increased irradiation didn't show any effect on beef redness. Fat contents influenced a* values, but the influence was not big. As fat % increased a* values of nonirradiated control patties decreased at both 0 and 3 d of storage. At 7 d, fat % influence was not consistent, and at 14 d a* values of nonirradiated control increased as fat % increased. Ascorbic acid + α-tocopherol maintained the redness of irradiated patties at 0 and 3 d of storage, as storage period increased to 7 and 14 d, the effectiveness of the additive to keep the red color was decreased. Redness values of patties treated with sesamol were lower than those treated with ascorbic acid + α-tocopherol, with very few exceptions.

The yellowness (b* values) of beef were decreased by irradiation, regardless of fat contents, at 0 d only (Table 4). As storage period increased there was not much effect of irradiation on b* values. There was some effect of fat content on the b* values, especially at 14d, where patties with higher fat content had higher b* values. Ascorbic acid + α-tocopherol increased the yellowness of beef patties at 0 d and 3 d of storage, while during the rest of the storage there was not effect. There was a lot of interactions that affected b* values.

Color changes in irradiated dark meat can not be explained as the color change in light meat mainly because of the difference in pigment content between light and dark meat. Dark meat has about 10 times higher pigment than light meat. Amount of produced CO by irradiation, however, is similar in both meats (Kim and others 2002). So the percentage of CO-heme to the total meat pigment will be different. It will represent very small percentage of the dark meat pigment, while in case of light meat it will represent a larger percent.

Animal species, muscle type, irradiation dose, and packaging type are all factors that affect color changes in irradiated meat (Satterlee and others 1971; Luchsinger and others 1996; Ahn and others 1998). Light meat such as poultry and pork will produce pink color because of irradiation. Brown or gray is the color of dark meat after irradiation (Millar and others 1995; Nanke and others 1998; Ahn and others 1998; Kim and others 2002).

Irradiation increased the production of CO regardless of the fat contents (Table 5). The produced CO decreased over storage period where at 7d and 14d there was not any differences between irradiated and nonirradiated beef patties. Treating beef with additives influenced CO production, where treating patties with additives decreased the amount of produced CO, however, the decrease was not that big. Carbon monoxide production is an irradiation dose-dependent, and it is produced by all kind of meat, dark or light (Nam and Ahn, 2002; Lee and Ahn, 2004)

ORP values were influenced by fat content, irradiation, additives and storage (Table 6). Ascorbic acid + α-tocopherol was effective in lowering ORP values regardless of fat contents. The reducing power of ascorbic acid maintained lower ORP values until 3 d after irradiation. Sesamol + ascorbic acid + α-tocopherol had similar effect with slight differences. Fat contents influenced ORP values in nonirradiated patties, where ORP values decreased as fat contents increased. In irradiated sample the influence of fat content on ORP was inconsistent. Oxidation-reduction potential played an effective role in color change of meat, mainly because of the intensity of ferrous heme pigment which was stronger than that of ferric form. Because of its capability as reducing agent, ascorbic acid could inhibit the oxidation of myoglobin and thus prevent the development of brown color in nonirradiated meat (Wheeler and others 1996; Lee and others 1999; Sanchez-Escalante and others 2001).

**Volatiles production**

Volatiles profiles at 0 d are presented in Tables 7 to 9. Irradiation increased total volatiles regardless of fat contents or additive treatments. Irradiation did not produce any sulfur-containing compounds. Hydrocarbons, ketones, and aldehydes were all increased by irradiation. Alcohols, however, were not affected by irradiation. Nam and others (2004) showed that irradiation increased the amounts of total volatiles. Hexanal was the highest aldehydes produced by irradiation, especially from 20% fat beef. Toluene, a cyclo compound, was newly generated by irradiation. Hydrocarbons were the highest volatiles produced by irradiation regardless of fat contents. There was no great influence of fat contents on volatiles produced by irradiation. Ascorbic acid + α-tocopherol was effective not only in reducing aldehydes produced by irradiation, but also in inhibiting the production of those volatiles in nonirradiated beef. Other volatiles did not seem to be affected much with Ascorbic acid + α-tocopherol. Adding sesamol to ascorbic acid + α-tocopherol did not do any further reduction in aldehydes compounds at 0d.

At 3 d (Tables 10 to 12) total produced volatiles in irradiated beef increased, aldehydes were the main contributor to that increase where their amounts almost doubled, regardless of fat contents. Similar to 0 d, hexanal was the highest and most the increased aldehydes. Hexanal is a common indicator of lipid oxidation in meat (Ahn and others 1999) Ascorbic acid + ascorbic acid reduced aldehydes in total in irradiated beef and also was effective to inhibit the production of most of aldehydes in nonirradiated beef as well. Additionally it reduced the total volatiles produced by irradiation at 3d by about 40-50%.

At 7 d (Tables 13 to 15) ascorbic acid + α-tocopherol had the same effect that it had at 3d. Alcohols were another group of volatiles that contributed to the increased total volatiles at 7d in nonirradiated beef, with ethanol being the most increased alcohols. At 14 d (Tables 16 to 18), total volatiles in nonirradiated beef increased drastically and most of that increase was because of alcohols. Irradiated beef, however, produced higher amount of aldehydes and ascorbic acid + α-tocopherol were effective to reduces decrease those aldehydes.

The sulfur volatiles newly generated by irradiation were sulfur-methyl ester ethanethioic acid, dimethyl sulfide, dimethyl disulfide, and dimethyl trisulfide. The production of sulfur-containing volatiles were highly dependent upon irradiation dose (Ahn and others 2000a), and sulfur volatiles were responsible for the characteristic off-odor in irradiated meat although the amounts and compositions may be different depending on meat species and muscle types (Ahn and others 2001; Ahn 2002; Ahn and Lee 2002). The intensity of irradiation off-odor diminished over storage period as the sulfur volatiles disappeared during storage under aerobic conditions (Nam and Ahn 2003).

## Conclusions

Irradiation increased both lipid oxidation and total volatiles, especially aldehydes, in ground beef over the storage period of 14 d. Also, beef redness was reduced by irradiation. Ascorbic acid + α- tocopherol, however, was effective in controlling the effect of irradiation on lipid oxidation, volatile production and color changes. Fat contents up to 20% did not have any influences on those changes that occurred as a result of irradiation. Therefore using ground beef with up to 20% fat, added with ascorbic acid + α- tocopherol, would not affect quality changes after irradiation.

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Table 1. TBARS values of beef added with different additives and fat contents during storage at 4° C

(Unit: mg MDA/kg meat)

| | 10 % fat | | | 15 % fat | | | 20 % fat | | |
|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | IR | SEM | Non-IR | IR | SEM | Non-IR | IR | SEM |
| ***Day 0*** | | | | | | | | | |
| Cont. | $2.17^{a}$ | $2.41^{a}$ | 0.24 | $1.92^{a}$ | $2.11^{a}$ | 0.24 | $1.98^{a}$ | $2.19^{a}$ | 0.26 |
| A+E | $0.72^{b}$ | $0.9^{b}$ | 0.08 | $0.80^{b}$ | $0.96^{b}$ | 0.13 | $0.79^{b}$ | $0.98^{b}$ | 0.10 |
| A+E+S | $0.64^{b}$ | $0.71^{b}$ | 0.07 | $0.64^{b}$ | $0.73^{b}$ | 0.09 | $0.77^{b}$ | $0.81^{b}$ | 0.10 |
| SEM | 0.16 | 0.15 | | 0.15 | 0.18 | | 0.17 | 0.17 | |
| ***Day 3*** | | | | | | | | | |
| Cont. | $3.36^{a}$ | $4.10^{a}$ | 0.52 | $3.20^{a}$ | $4.10^{a}$ | 0.27 | $3.11^{ay}$ | $4.31^{ax}$ | 0.25 |
| A+E | $0.87^{b}$ | $1.12^{b}$ | 0.14 | $0.76^{b}$ | $0.90^{b}$ | 0.20 | $0.93^{b}$ | $1.33^{b}$ | 0.32 |
| A+E+S | $0.66^{b}$ | $0.69^{b}$ | 0.07 | $0.69^{b}$ | $0.72^{b}$ | 0.05 | $0.76^{b}$ | $0.88^{b}$ | 0.11 |
| SEM | 0.37 | 0.25 | | 0.13 | 0.25 | | 0.20 | 0.28 | |
| ***Day 7*** | | | | | | | | | |
| Cont. | $6.53^{a}$ | $5.82^{a}$ | 0.38 | $4.30^{ay}$ | $6.28^{ax}$ | 0.43 | $5.15^{a}$ | $5.25^{a}$ | 0.62 |
| A+E | $1.76^{by}$ | $2.99^{bx}$ | 0.24 | $1.56^{b}$ | $2.19^{b}$ | 0.42 | $2.37^{b}$ | $1.76^{b}$ | 0.27 |
| A+E+S | $0.71^{c}$ | $0.69^{c}$ | 0.08 | $0.67^{by}$ | $1.10^{cx}$ | 0.06 | $0.85^{b}$ | $0.65^{c}$ | 0.11 |
| SEM | 0.20 | 0.32 | | 0.27 | 0.41 | | 0.49 | 0.27 | |
| ***Day 14*** | | | | | | | | | |
| Cont. | $5.62^{a}$ | $7.52^{a}$ | 0.60 | $4.55^{ay}$ | $7.26^{ax}$ | 0.40 | $4.98^{ay}$ | $8.16^{ax}$ | 0.62 |
| A+E | $2.9^{b}$ | $3.79^{b}$ | 0.45 | $2.35^{b}$ | $2.60^{b}$ | 0.40 | $2.48^{b}$ | $3.15^{b}$ | 0.21 |
| A+E+S | $0.59^{by}$ | $1.82^{cx}$ | 0.22 | $0.64^{by}$ | $1.76^{cx}$ | 0.19 | $0.72^{cy}$ | $1.46^{cx}$ | 0.18 |
| SEM | 0.36 | 0.53 | | 0.34 | 0.35 | | 0.19 | 0.52 | |

| | DF | F value | P |
|---|---|---|---|
| Fat % (F) | 2 | 4.48 | 0.0124 |
| Irradiation (IR) | 1 | 18.99 | 0.0001 |
| Additives (AD) | 2 | 914.61 | 0.0001 |
| Storage (S) | 3 | 195.44 | 0.0001 |
| F x IR | 2 | 2.48 | 0.0863 |
| F x AD | 4 | 1.81 | 0.1275 |
| F x S | 6 | 1.32 | 0.2515 |
| IR x AD | 2 | 30.11 | 0.0001 |
| IR x S | 3 | 5.57 | 0.0011 |
| AD x S | 6 | 51.08 | 0.0001 |
| F x IR x AD | 4 | 1.41 | 0.2302 |
| F x IR x S | 6 | 2.42 | 0.0279 |
| F x AD x S | 12 | 0.77 | 0.6818 |
| IR x AD x S | 6 | 10.23 | 0.0001 |
| F x IR x AD x S | 12 | 1.11 | 0.3572 |

$^{a-c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)

$^{x-y}$ Values with different letters within a row of each fat % are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 2 CIE color L-values of beef with different additives, fat contents, and storage times at 4° C

| | 10 % fat | | | | | 15 % fat | | | | | 20 % fat | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | | IR | | | Non-IR | | IR | | | Non-IR | | IR | | |
| | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM |
| ***Day 0*** | | | | | | | | | | | | | | | |
| Cont. | 51.5$^{w}$ | 49.6b$^{x}$ | 48.4$^{x}$ | 47.9x | 0.5 | 52.8$^{w}$ | 50.8$^{x}$ | 50.1$^{x}$ | 49.1$^{x}$ | 0.6 | 53.7$^{uw}$ | 53.7$^{uw}$ | 51.1$^{x}$ | 51.7$^{x}$ | 0.5 |
| A+E | 51.8$^{w}$ | 51.9$^{aw}$ | 47.9$^{x}$ | 46.9$^{x}$ | 0.6 | 52.4$^{w}$ | 51.8$^{w}$ | 48.7$^{x}$ | 48.4$^{x}$ | 0.8 | 55.0$^{w}$ | 54.1$^{w}$ | 52.1$^{x}$ | 50.8$^{x}$ | 0.6 |
| A+E+S | 50.8$^{w}$ | 49.6$^{bx}$ | 47.3$^{y}$ | 46.6$^{y}$ | 0.4 | 51.8$^{w}$ | 50.7$^{wx}$ | 48.6$^{y}$ | 49.1$^{xy}$ | 0.6 | 53.9$^{w}$ | 53.7$^{w}$ | 50.8$^{x}$ | 50.6$^{x}$ | 0.6 |
| SEM | 0.3 | 0.4 | 0.7 | 0.5 | | 0.6 | 0.6 | 0.7 | 0.7 | 0.6 | 0.5 | 0.5 | 0.6 | | |
| ***Day 3*** | | | | | | | | | | | | | | | |
| Cont. | 50.7$^{w}$ | 49.3$^{awx}$ | 49.9$^{awx}$ | 47.8$^{x}$ | 0.7 | 51.0$^{a}$ | 50.1 | 50.1 | 49.4 | 0.8 | 50.8$^{w}$ | 52.3$^{wx}$ | 53.9$^{aw}$ | 52.0$^{awx}$ | 0.6 |
| A+E | 49.9 | 49.9$^{a}$ | 50.5$^{a}$ | 48.2 | 0.6 | 51.4$^{a}$ | 50.2 | 50.0 | 49.7 | 0.7 | 51.2 | 51.9 | 49.9$^{b}$ | 50.7$^{b}$ | 0.8 |
| A+E+S | 49.1$^{w}$ | 47.5$^{bx}$ | 46.5$^{bx}$ | 46.3$^{x}$ | 0.4 | 48.2$^{b}$ | 48.8 | 50.1 | 48.7 | 0.9 | 51.1 | 50.6 | 49.9$^{b}$ | 50.3$^{b}$ | 0.7 |
| SEM | 0.8 | 0.4 | 0.5 | 0.6 | | 0.8 | 0.5 | 1.2 | 0.7 | | 0.8 | 0.5 | 0.9 | 0.4 | |
| ***Day 7*** | | | | | | | | | | | | | | | |
| Cont. | 45.8 | 47.9 | 48.9 | 48.9$^{a}$ | 1.2 | 49.7$^{a}$ | 50.8$^{a}$ | 50.7$^{a}$ | 50.2$^{a}$ | 0.8 | 52.0$^{ax}$ | 51.7$^{x}$ | 53.5$^{aw}$ | 52.3$^{ax}$ | 0.4 |
| A+E | 47.6 | 47.5 | 47.4 | 46.8$^{b}$ | 1.3 | 51.2$^{aw}$ | 51.7$^{aw}$ | 50.5$^{aw}$ | 47.5$^{bx}$ | 0.8 | 52.0$^{aw}$ | 51.9$^{w}$ | 48.3$^{bx}$ | 50.5$^{bwx}$ | 0.7 |
| A+E+S | 46.5 | 46.4 | 46.3 | 44.6$^{c}$ | 0.8 | 46.6$^{bwx}$ | 48.7$^{bw}$ | 45.7$^{bx}$ | 47.7$^{bwx}$ | 0.6 | 46.1$^{bx}$ | 51.1$^{w}$ | 48.6$^{bwx}$ | 49.9$^{bwx}$ | 1.2 |
| SEM | 1.5 | 0.5 | 1.4 | 0.3 | | 0.9 | 0.7 | 0.7 | 0.6 | | 0.9 | 0.5 | 1.2 | 0.4 | |
| ***Day 14*** | | | | | | | | | | | | | | | |
| Cont. | 45.7$^{y}$ | 48.3$^{ax}$ | 50.7$^{aw}$ | 50.9$^{aw}$ | 0.7 | 46.9$^{x}$ | 48.4$^{x}$ | 52.8$^{aw}$ | 52.2$^{aw}$ | 0.7 | 50.3$^{abx}$ | 51.8$^{wx}$ | 54.8$^{w}$ | 54.1$^{awx}$ | 1.1 |
| A+E | 45.2 | 46.7$^{b}$ | 48.9$^{ab}$ | 48$^{b}$ | 0.8 | 49.1 | 49.1 | 50.4$^{a}$ | 49.0$^{b}$ | 1.0 | 52.6$^{a}$ | 51.4 | 54.4 | 51.7$^{b}$ | 1.0 |
| A+E+S | 44.3$^{x}$ | 45.3$^{cx}$ | 46.6$^{bw}$ | 47.4$^{bw}$ | 0.4 | 45.7 | 48.6 | 45.4$^{b}$ | 48.5$^{b}$ | 0.8 | 48.2$^{bx}$ | 50.1$^{wx}$ | 50.9$^{w}$ | 50.6$^{bw}$ | 0.7 |
| SEM | 0.8 | 0.3 | 0.9 | 0.3 | | 0.9 | 0.7 | 1.0 | 0.6 | | 0.9 | 0.6 | 1.5 | 0.4 | |

| | **DF** | **F value** | **P** | | **DF** | **F value** | **P** |
|---|---|---|---|---|---|---|---|
| Fat % (F) | 2 | 71.66 | 0.0001 | IR x S | 3 | 32.99 | 0.0001 |
| Irradiation (IR) | 1 | 0.06 | 0.8088 | AD x S | 6 | 3.71 | 0.0013 |
| Additives (AD) | 2 | 45.79 | 0.0001 | F x IR x AD | 4 | 1.17 | 0.3238 |
| Storage (S) | 3 | 23.40 | 0.0001 | F x IR x S | 6 | 0.63 | 0.7036 |
| F x IR | 2 | 0.35 | 0.7020 | F x AD x S | 12 | 2.13 | 0.0141 |
| F x AD | 4 | 1.10 | 0.3559 | IR x AD x S | 6 | 1.34 | 0.2382 |
| F x S | 6 | 3.95 | 0.0007 | F x IR x AD x S | 12 | 1.64 | 0.0771 |
| IR x AD | 2 | 8.06 | 0.0004 | | | | |

$^{a\text{-}c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)

$^{w\text{-}z}$ Values with different letters within a row of each fat % are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 3. CIE color a-values of beef with different additives, fat contents, and storage times at 4° C

| | 10 % fat | | | | | 15 % fat | | | | | 20 % fat | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | | IR | | | Non-IR | | IR | | | Non-IR | | IR | | |
| | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM |
| ***Day 0*** | | | | | | | | | | | | | | | |
| Cont. | 24.8$^{cw}$ | 24.4$^{bw}$ | 14.5$^{cx}$ | 14.8$^{bx}$ | 0.7 | 25.5$^{cw}$ | 24.8$^{cw}$ | 14.9$^{cy}$ | 15.9$^{bx}$ | 0.3 | 26.2$^{w}$ | 23.7$^{cx}$ | 15.5$^{cy}$ | 15.2$^{cy}$ | 0.5 |
| A+E | 28.7$^{aw}$ | 27.7$^{aw}$ | 16.8$^{bx}$ | 17.2$^{ax}$ | 0.4 | 29.9$^{aw}$ | 29.4$^{aw}$ | 17.5$^{bx}$ | 17.4$^{ax}$ | 0.4 | 27.8$^{w}$ | 27.7$^{aw}$ | 16.5$^{bx}$ | 17.2$^{bx}$ | 0.4 |
| A+E+S | 26.7$^{bw}$ | 26.2$^{abw}$ | 18.0$^{ax}$ | 18.1$^{ax}$ | 0.3 | 27.4$^{bw}$ | 26.7$^{bw}$ | 18.9$^{ax}$ | 17.7$^{ax}$ | 0.4 | 26.5$^{w}$ | 25.2$^{bw}$ | 19.3$^{ax}$ | 19.5$^{ax}$ | 0.6 |
| SEM | 0.5 | 0.6 | 0.3 | 0.4 | | 0.4 | 0.5 | 0.3 | 0.4 | | 0.5 | 0.5 | 0.3 | 0.5 | |
| ***Day 3*** | | | | | | | | | | | | | | | |
| Cont | 14.8$^{cw}$ | 15.7$^{cw}$ | 11.3$^{bx}$ | 13.1$^{bwx}$ | 0.8 | 11.5$^{cx}$ | 13.9$^{cw}$ | 11.2$^{cx}$ | 12.5$^{bx}$ | 0.5 | 10.9$^{c}$ | 11.9$^{c}$ | 11.4$^{b}$ | 12.3$^{c}$ | 0.5 |
| A+E | 26.3$^{aw}$ | 26.2$^{aw}$ | 20.2$^{ax}$ | 21.5$^{ax}$ | 0.5 | 27.3$^{aw}$ | 27.5$^{aw}$ | 21.4$^{ax}$ | 21.3$^{ax}$ | 0.5 | 26.3$^{aw}$ | 26.1$^{aw}$ | 21.4$^{ax}$ | 21.9$^{ax}$ | 0.6 |
| A+E+S | 20.9$^{bx}$ | 22.6$^{bw}$ | 19.9$^{ax}$ | 20.5$^{ax}$ | 0.4 | 20.5$^{bx}$ | 22.5$^{bw}$ | 18.9$^{by}$ | 20.3$^{ax}$ | 0.4 | 19$^{bx}$ | 21.8$^{bw}$ | 20.2$^{awx}$ | 20.9$^{bw}$ | 0.5 |
| SEM | 0.8 | 0.7 | 0.3 | 0.4 | | 0.4 | 0.5 | 0.5 | 0.5 | | 0.6 | 0.5 | 0.6 | 0.3 | |
| ***Day 7*** | | | | | | | | | | | | | | | |
| Cont | 9.8$^{abx}$ | 11.1$^{w}$ | 9.7$^{bx}$ | 10.0$^{cx}$ | 0.2 | 9.4$^{bx}$ | 10.3$^{w}$ | 9.8$^{cwx}$ | 9.9$^{cwx}$ | 0.2 | 9.7$^{bx}$ | 10.8$^{w}$ | 9.7$^{cx}$ | 10.3$^{cwx}$ | 0.2 |
| A+E | 9.5$^{bz}$ | 11.2$^{y}$ | 13.6$^{ax}$ | 19.9$^{aw}$ | 0.5 | 9.9$^{ay}$ | 9.9$^{y}$ | 16.7$^{ax}$ | 21.7$^{aw}$ | 0.6 | 9.3$^{by}$ | 10.7$^{y}$ | 17.1$^{ax}$ | 20.3$^{aw}$ | 0.6 |
| A+E+S | 10.4$^{ay}$ | 11.2$^{y}$ | 14.2$^{ax}$ | 18.8$^{bw}$ | 0.3 | 10.3$^{ay}$ | 10.0$^{y}$ | 12.6$^{bx}$ | 18.2$^{bw}$ | 0.3 | 10.7$^{ay}$ | 10.2$^{y}$ | 14.1$^{bx}$ | 17.7$^{bw}$ | 0.4 |
| SEM | 0.2 | 0.3 | 0.6 | 0.2 | | 0.1 | 0.2 | 0.7 | 0.4 | | 0.3 | 0.3 | 0.7 | 0.3 | |
| ***Day 14*** | | | | | | | | | | | | | | | |
| Cont | 10.8$^{x}$ | 13.2$^{w}$ | 9.5$^{bx}$ | 9.4$^{bx}$ | 0.7 | 11.4$^{bx}$ | 15.5$^{aw}$ | 9.2$^{by}$ | 9.5$^{cy}$ | 0.4 | 13.4$^{w}$ | 15.1$^{w}$ | 9.3$^{bx}$ | 9.6$^{cx}$ | 0.7 |
| A+E | 9.7$^{x}$ | 12.2$^{w}$ | 9.6$^{bx}$ | 14.1$^{aw}$ | 0.6 | 12.6$^{ay}$ | 14.5$^{ax}$ | 11.2$^{ay}$ | 16.9$^{aw}$ | 0.6 | 12.2$^{x}$ | 16.9$^{w}$ | 9.8$^{by}$ | 15.8$^{aw}$ | 0.5 |
| A+E+S | 11.1$^{x}$ | 11.2$^{x}$ | 10.8$^{ax}$ | 14.1$^{auv}$ | 0.5 | 13.5$^{aw}$ | 12.8$^{bw}$ | 9.3$^{bx}$ | 12.6$^{bw}$ | 0.4 | 11.9$^{x}$ | 14.4$^{w}$ | 10.6$^{ay}$ | 13.8$^{bw}$ | 0.4 |
| SEM | 0.7 | 0.8 | 0.4 | 0.4 | | 0.4 | 0.6 | 0.4 | 0.5 | | 0.5 | 0.9 | 0.2 | 0.2 | |

| | **DF** | **F value** | **P** | | **DF** | **F value** | **P** |
|---|---|---|---|---|---|---|---|
| Fat % (F) | 2 | 4.77 | 0.0089 | IR x S | 3 | 576.37 | 0.0001 |
| Irradiation (IR) | 1 | 613.87 | 0.0001 | AD x S | 6 | 172.19 | 0.0001 |
| Additives (AD) | 2 | 553.05 | 0.0001 | F x IR x AD | 4 | 4.03 | 0.0032 |
| Storage (S) | 3 | 2247.13 | 0.0001 | F x IR x S | 6 | 5.96 | 0.0001 |
| F x IR | 2 | 3.44 | 0.0327 | F x AD x S | 12 | 2.41 | 0.0048 |
| F x AD | 4 | 8.44 | 0.0001 | IR x AD x S | 6 | 38.22 | 0.0001 |
| F x S | 6 | 4.28 | 0.0003 | F x IR x AD x S | 12 | 2.05 | 0.0186 |
| IR x AD | 2 | 20.00 | 0.0001 | | | | |

$^{a\text{-}c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)

$^{w\text{-}z}$ Values with different letters within a row of each fat %are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 4. CIE color b-values of beef with different additives, fat contents, and storage times at 4° C

| | 10 % fat | | | | | 15 % fat | | | | | 20 % fat | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | | IR | | | Non-IR | | IR | | | Non-IR | | IR | | |
| | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM |
| ***Day 0*** | | | | | | | | | | | | | | | |
| Cont | 21.2$^{bw}$ | 22.2$^{w}$ | 15.9$^{bx}$ | 16.9$^{x}$ | 0.6 | 22.3$^{cw}$ | 22.7$^{bw}$ | 17.7$^{bx}$ | 18.7$^{x}$ | 0.4 | 23.8$^{w}$ | 21.6$^{bx}$ | 18.5$^{aby}$ | 18.5$^{y}$ | 0.5 |
| A+E | 23.5$^{aw}$ | 23.4$^{w}$ | 16.9$^{abx}$ | 17.5$^{x}$ | 0.4 | 26.1$^{aw}$ | 26.2$^{aw}$ | 18.5$^{ax}$ | 18.4$^{x}$ | 0.5 | 24.2$^{w}$ | 24.3$^{aw}$ | 17.6$^{bx}$ | 17.9$^{x}$ | 0.4 |
| A+E+S | 22.7$^{abw}$ | 23.4$^{w}$ | 17.9$^{ax}$ | 17.9$^{x}$ | 0.4 | 24.4$^{bw}$ | 23.9$^{bw}$ | 19.1$^{ax}$ | 18.1$^{x}$ | 0.4 | 24.2$^{w}$ | 22.9$^{abw}$ | 19.5$^{ax}$ | 19.4$^{x}$ | 0.6 |
| SEM | 0.6 | 0.6 | 0.4 | 0.4 | | 0.5 | 0.6 | 0.3 | 0.4 | | 0.5 | 0.5 | 0.5 | 0.6 | |
| ***Day 3*** | | | | | | | | | | | | | | | |
| Cont | 18.4$^{cw}$ | 18.9$^{bw}$ | 16.4$^{cx}$ | 18.6$^{bw}$ | 0.5 | 18.9$^{c}$ | 19.9$^{c}$ | 18.5$^{b}$ | 19.3$^{b}$ | 0.4 | 19.9$^{b}$ | 19.5$^{c}$ | 19.4$^{b}$ | 19.4$^{b}$ | 0.5 |
| A+E | 22.5$^{aw}$ | 23.2$^{aw}$ | 18.5$^{by}$ | 20.6$^{ax}$ | 0.6 | 24.6$^{aw}$ | 24.6$^{aw}$ | 21.3$^{ax}$ | 21.0$^{ax}$ | 0.6 | 24.3$^{aw}$ | 24.6$^{aw}$ | 20.7$^{ay}$ | 22.0$^{ax}$ | 0.4 |
| A+E+S | 20.5$^{bx}$ | 22.3$^{aw}$ | 20.6$^{ax}$ | 21.0$^{awx}$ | 0.5 | 20.5$^{bx}$ | 22.7$^{bw}$ | 20.4$^{ax}$ | 20.9$^{ax}$ | 0.4 | 20.2$^{bx}$ | 22.7$^{bw}$ | 21.4$^{awx}$ | 22.0$^{awx}$ | 0.5 |
| SEM | 0.6 | 0.5 | 0.5 | 0.5 | | 0.5 | 0.5 | 0.4 | 0.4 | | 0.6 | 0.6 | 0.4 | 0.2 | |
| ***Day 7*** | | | | | | | | | | | | | | | |
| Cont | 18.7$^{x}$ | 21.4$^{aw}$ | 19.3$^{x}$ | 20.3$^{wx}$ | 0.5 | 19.5$^{a}$ | 21.1$^{a}$ | 19.9 | 20.4$^{b}$ | 0.4 | 19.9 | 21.6$^{a}$ | 20.3 | 20.7 | 0.4 |
| A+E | 18.7$^{x}$ | 20.0$^{bw}$ | 18.0x | 21.1$^{w}$ | 0.8 | 19.7$^{ax}$ | 19.6$^{bx}$ | 19.7$^{x}$ | 22.6$^{aw}$ | 0.6 | 19.2$^{x}$ | 19.9$^{bx}$ | 19.6$^{x}$ | 21.5$^{w}$ | 0.5 |
| A+E+S | 18.7$^{x}$ | 19.7$^{bx}$ | 18.8$^{x}$ | 21.6$^{w}$ | 0.3 | 18.1$^{bx}$ | 19.3$^{bx}$ | 18.4$^{x}$ | 20.8$^{bw}$ | 0.4 | 19.4$^{x}$ | 19.1$^{bx}$ | 19.2$^{x}$ | 21.1$^{w}$ | 0.3 |
| SEM | 0.5 | 0.3 | 0.4 | 0.4 | | 0.4 | 0.4 | 0.6 | 0.5 | | 0.4 | 0.5 | 0.5 | 0.3 | |
| ***Day 14*** | | | | | | | | | | | | | | | |
| Cont | 18.8$^{x}$ | 21.3$^{aw}$ | 19.7$^{ax}$ | 20.2$^{awx}$ | 0.4 | 20.7$^{x}$ | 23.0$^{aw}$ | 19.4$^{ay}$ | 20.2$^{axy}$ | 0.4 | 22.7$^{aw}$ | 22.3$^{aw}$ | 19.9$^{x}$ | 20.9$^{ax}$ | 0.4 |
| A+E | 17.9$^{x}$ | 20.0$^{bw}$ | 17.5$^{bx}$ | 19.2$^{bwx}$ | 0.5 | 21.4$^{w}$ | 20.9$^{bw}$ | 17.9$^{ax}$ | 19.9$^{aw}$ | 0.4 | 21.1$^{bw}$ | 21.1$^{abw}$ | 17.9$^{x}$ | 19.9$^{bw}$ | 0.4 |
| A+E+S | 19.4$^{w}$ | 19.1$^{bw}$ | 16.5$^{bx}$ | 18.6$^{bw}$ | 0.5 | 20.4$^{w}$ | 18.7$^{cx}$ | 14.9$^{by}$ | 17.9$^{bx}$ | 0.6 | 20.2$^{bw}$ | 20.1$^{bw}$ | 18.3$^{x}$ | 19.6$^{bw}$ | 0.4 |
| SEM | 0.7 | 0.3 | 0.5 | 0.3 | | 0.4 | 0.3 | 0.6 | 0.4 | | 0.3 | 0.4 | 0.6 | 0.3 | |

| | DF | F value | P | | DF | F value | P |
|---|---|---|---|---|---|---|---|
| Fat % (F) | 2 | 54.02 | 0.0001 | IR x S | 3 | 110.30 | 0.0001 |
| Irradiation (IR) | 1 | 386.23 | 0.0001 | AD x S | 6 | 33.31 | 0.0001 |
| Additives (AD) | 2 | 14.48 | 0.0001 | F x IR x AD | 4 | 1.81 | 0.1258 |
| Storage (S) | 3 | 51.25 | 0.0001 | F x IR x S | 6 | 3.89 | 0.0008 |
| F x IR | 2 | 1.60 | 0.2022 | F x AD x S | 12 | 1.09 | 0.3653 |
| F x AD | 4 | 9.81 | 0.0001 | IR x AD x S | 6 | 8.29 | 0.0001 |
| F x S | 6 | 2.29 | 0.0346 | F x IR x AD x S | 12 | 1.40 | 0.1624 |
| IR x AD | 2 | 17.28 | 0.0001 | | | | |

$^{a\text{-}c}$ Values with different letters within a column of each storage period are significantly different (*P*<0.05)

$^{w\text{-}z}$ Values with different letters within a row of each fat %are significantly different (*P*<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 5. Carbon monoxide (CO) gas formation from irradiated beef with different additives, fat contents, and storage times at 4° C

(Unit: ppm)

| | 10 % fat | | | 15 % fat | | | 20 % fat | | |
|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | IR | SEM | Non-IR | IR | SEM | Non-IR | IR | SEM |
| ***Day 0*** | | | | | | | | | |
| Cont. | 86.32$^{a}$ | 132.46 | 13.98 | 60.62$^{y}$ | 144.82$^{x}$ | 8.06 | 52.08$^{y}$ | 146.03$^{x}$ | 15.27 |
| A+E | 37.92$^{by}$ | 101.22$^{x}$ | 10.07 | 39.64$^{y}$ | 116.42$^{x}$ | 11.50 | 42.36$^{y}$ | 118.66$^{x}$ | 6.50 |
| A+E+S | 43.85$^{by}$ | 110.92$^{x}$ | 7.39 | 45.06$^{y}$ | 100.40$^{x}$ | 10.15 | 48.49$^{y}$ | 143.83$^{x}$ | 13.47 |
| SEM | 9.23 | 12.21 | | 7.47 | 12.01 | | 7.59 | 15.72 | |
| ***Day 3*** | | | | | | | | | |
| Cont. | 53.41$^{y}$ | 106.36$^{x}$ | 9.29 | 47.44$^{ay}$ | 126.57$^{ax}$ | 14.98 | 38.51$^{y}$ | 97.86$^{x}$ | 10.25 |
| A+E | 34.50 | 87.13 | 15.26 | 37.32$^{aby}$ | 87.28$^{abx}$ | 8.17 | 21.89$^{y}$ | 83.90$^{x}$ | 10.36 |
| A+E+S | 36.84$^{y}$ | 84.06$^{x}$ | 4.32 | 28.72$^{by}$ | 64.57$^{bx}$ | 3.41 | 17.67$^{y}$ | 85.06$^{x}$ | 4.87 |
| SEM | 6.19 | 13.67 | | 4.65 | 13.42 | | 6.58 | 10.68 | |
| ***Day 7*** | | | | | | | | | |
| Cont. | 26.69$^{y}$ | 58.9$^{abx}$ | 8.06 | 46.50$^{y}$ | 78.30$^{ax}$ | 5.15 | 28.37 | 60.68 | 10.56 |
| A+E | 27.45$^{y}$ | 83.73$^{ax}$ | 6.19 | 28.1y$^{y}$ | 76.99$^{ax}$ | 7.19 | 20.06$^{y}$ | 62.26$^{x}$ | 2.72 |
| A+E+S | 34.70 | 40.68$^{b}$ | 7.12 | 26.95 | 34.65$^{b}$ | 6.40 | 12.14$^{y}$ | 63.87$^{x}$ | 4.47 |
| SEM | 5.53 | 8.49 | | 5.89 | 6.69 | | 6.91 | 6.70 | |
| ***Day 14*** | | | | | | | | | |
| Cont. | 26.36 | 41.07 | 4.53 | 32.86 | 54.64 | 10.04 | 21.29$^{y}$ | 52.33$^{x}$ | 3.56 |
| A+E | 26.12$^{y}$ | 45.58$^{x}$ | 4.21 | 20.84$^{y}$ | 65.50$^{x}$ | 9.35 | 18.45$^{y}$ | 58.92$^{x}$ | 3.08 |
| A+E+S | 26.98 | 36.9 | 8.90 | 23.84 | 30.95 | 4.43 | 11.86$^{y}$ | 47.41$^{x}$ | 8.89 |
| SEM | 7.77 | 4.24 | | 5.33 | 10.49 | | 2.53 | 7.82 | |

| | DF | F value | P |
|---|---|---|---|
| Fat % (F) | 2 | 0.58 | 0.5598 |
| Irradiation (IR) | 1 | 510.31 | 0.0001 |
| Additives (AD) | 2 | 24.16 | 0.0001 |
| Storage (S) | 3 | 118.95 | 0.0001 |
| F x IR | 2 | 6.64 | 0.0016 |
| F x AD | 4 | 3.18 | 0.0145 |
| F x S | 6 | 1.34 | 0.2394 |
| IR x AD | 2 | 2.97 | 0.0535 |
| IR x S | 3 | 26.97 | 0.0001 |
| AD x S | 6 | 4.34 | 0.0004 |
| F x IR x AD | 4 | 3.02 | 0.0189 |
| F x IR x S | 6 | 0.43 | 0.8562 |
| F x AD x S | 12 | 0.77 | 0.6777 |
| IR x AD x S | 6 | 1.05 | 0.3940 |
| F x IR x AD x S | 12 | 0.68 | 0.7667 |

$^{a-c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)

$^{w-y}$ Values with different letters within a row of each fat % are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 6. Oxidation-reduction potential (ORP) values of beef added with different additives and fat contents during storage at 4° C

(Unit: mVolt)

| | 10 % fat | | | 15 % fat | | | 20 % fat | | |
|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | IR | SEM | Non-IR | IR | SEM | Non-IR | IR | SEM |
| ***Day 0*** | | | | | | | | | |
| Cont. | 90.08$^{a}$ | 107.20$^{a}$ | 8.00 | 81.48$^{a}$ | 97.93$^{a}$ | 8.86 | 81.05$^{a}$ | 94.65$^{a}$ | 17.31 |
| A+E | 22.65$^{b}$ | 26.93$^{b}$ | 1.82 | 16.93$^{b}$ | 10.58$^{b}$ | 3.20 | 9.10$^{b}$ | 13.40$^{b}$ | 4.12 |
| A+E+S | 19.73$^{b}$ | 20.88$^{b}$ | 4.04 | 15.18$^{b}$ | 13.98$^{b}$ | 3.88 | 14.53$^{b}$ | 18.20$^{b}$ | 4.78 |
| SEM | 5.21 | 5.34 | | 5.57 | 6.18 | | 10.07 | 11.18 | |
| ***Day 3*** | | | | | | | | | |
| Cont. | 118.38$^{a}$ | 121.28$^{a}$ | 10.33 | 97.8$^{ay}$ | 156.55$^{ax}$ | 16.06 | 84.00$^{ay}$ | 135.60$^{ax}$ | 11.63 |
| A+E | 58.68$^{b}$ | 36.43$^{b}$ | 12.83 | 39.00$^{by}$ | 78.28x | 6.24 | 27.58$^{by}$ | 109.48$^{ax}$ | 2.15 |
| A+E+S | 22.92$^{b}$ | 44.03$^{b}$ | 9.11 | 88.73$^{a}$ | 92.90$^{b}$ | 6.93 | 56.53$^{ab}$ | 85.63$^{b}$ | 12.55 |
| SEM | 11.45 | 10.25 | | 14.35 | 4.91 | | 11.16 | 8.59 | |
| ***Day 7*** | | | | | | | | | |
| Cont. | 136.03$^{a}$ | 180.55$^{a}$ | 13.63 | 83.33 | 134.03 | 18.27 | 44.40$^{y}$ | 131.78$^{ax}$ | 8.83 |
| A+E | 66.80$^{by}$ | 131.68$^{bx}$ | 15.79 | 80.55 | 102.60 | 9.45 | 43.13$^{x}$ | 83.98$^{bz}$ | 11.69 |
| A+E+S | 97.83$^{aby}$ | 131.65$^{x}$ | 5.13 | 85.25 | 107.20 | 9.46 | 33.88$^{y}$ | 90.93$^{bx}$ | 9.87 |
| SEM | 16.02 | 7.14 | | 11.15 | 14.77 | | 11.68 | 8.45 | |
| ***Day 14*** | | | | | | | | | |
| Cont. | -6.10$^{y}$ | 171.18$^{x}$ | 37.26 | -3.60$^{y}$ | 152.65$^{x}$ | 15.76 | -19.10$^{y}$ | 160.48$^{x}$ | 28.62 |
| A+E | 70.05$^{y}$ | 168.70$^{x}$ | 17.03 | 22.28 | 128.85$^{x}$ | 15.71 | 1.05$^{y}$ | 155.98$^{x}$ | 5.42 |
| A+E+S | 48.33$^{y}$ | 157.80$^{x}$ | 15.81 | 11.83$^{y}$ | 135.60$^{x}$ | 13.49 | -20.25$^{y}$ | 134.68$^{ax}$ | 12.13 |
| SEM | 35.04 | 7.63 | | 18.42 | 10.58 | | 21.85 | 13.65 | |

| | DF | F value | Pr |
|---|---|---|---|
| Fat % (F) | 2 | 13.13 | 0.0001 |
| Irradiation (IR) | 1 | 313.31 | 0.0001 |
| Additives (AD) | 2 | 66.78 | 0.0001 |
| Storage (S) | 3 | 57.42 | 0.0001 |
| F x IR | 2 | 6.48 | 0.0018 |
| F x AD | 4 | 1.06 | 0.3793 |
| F x S | 6 | 9.04 | 0.0001 |
| IR x AD | 2 | 6.26 | 0.0023 |
| IR x S | 3 | 87.35 | 0.0001 |
| AD x S | 6 | 15.67 | 0.0001 |
| F x IR x AD | 4 | 0.35 | 0.8413 |
| F x IR x S | 6 | 1.67 | 0.1293 |
| F x AD x S | 12 | 1.67 | 0.0747 |
| IR x AD x S | 6 | 0.90 | 0.4948 |
| F x IR x AD x S | 12 | 1.16 | 0.3139 |

$^{a-c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)

$^{x-y}$ Values with different letters within a row of each fat % are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 7. Volatile compounds of beef added with 10% fat and different additives after 0 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | (Total ion counts x $10^4$) | | | | | | |
| ***Hydrocarbons*** | ***5317$^{c}$*** | ***13994$^{a}$*** | ***5256$^{c}$*** | ***12410$^{a}$*** | ***5255$^{c}$*** | ***10033$^{b}$*** | ***1224*** |
| 2-Methyl-butane | 430$^{ab}$ | 973$^{a}$ | 459$^{ab}$ | 790$^{ab}$ | 854$^{ab}$ | 343$^{b}$ | 127 |
| Pentane | 3807$^{b}$ | 6401$^{a}$ | 1238$^{d}$ | 2417$^{c}$ | 899$^{d}$ | 1725$^{cd}$ | 285 |
| Pentene | 0$^{b}$ | 326$^{a}$ | 0$^{b}$ | 342$^{a}$ | 0$^{b}$ | 287$^{a}$ | 23 |
| Hexane | 803$^{c}$ | 2105$^{b}$ | 3269$^{ab}$ | 4592$^{a}$ | 3252$^{ab}$ | 3963$^{a}$ | 390 |
| 1-Heptene | 0$^{b}$ | 394$^{a}$ | 0$^{b}$ | 325$^{a}$ | 0$^{b}$ | 313$^{a}$ | 21 |
| Heptane | 0$^{b}$ | 1814$^{a}$ | 0$^{b}$ | 1835$^{a}$ | 0$^{b}$ | 1422$^{a}$ | 117 |
| Octane | 274$^{b}$ | 1448$^{a}$ | 288$^{b}$ | 1557$^{a}$ | 249$^{b}$ | 1397$^{a}$ | 101 |
| Nonane | 0$^{b}$ | 259$^{a}$ | 0$^{b}$ | 250$^{a}$ | 0$^{b}$ | 302$^{a}$ | 23 |
| ***Ketones*** | ***5176$^{c}$*** | ***8917$^{ab}$*** | ***5996$^{bc}$*** | ***11917$^{a}$*** | ***5936$^{bc}$*** | ***11076$^{a}$*** | ***710*** |
| 2-Propanone | 4310 | 4745 | 4691 | 5449 | 4518 | 4956 | 446 |
| 2,3-Butanedione | 695$^{c}$ | 1038$^{c}$ | 1101$^{abc}$ | 1678$^{a}$ | 1203$^{abc}$ | 1478$^{ab}$ | 147 |
| 2-Butanone | 170$^{c}$ | 3132$^{b}$ | 202$^{c}$ | 4789$^{a}$ | 215$^{c}$ | 4642$^{a}$ | 380 |
| ***Alcohols*** | ***6267*** | ***6643*** | ***3327*** | ***5566*** | ***3977*** | ***9258*** | ***1528*** |
| Ethanol | 4050 | 3435 | 1831 | 3755 | 2668 | 7771 | 1344 |
| 1-Propanol | 154$^{bc}$ | 177$^{a}$ | 0$^{e}$ | 159$^{b}$ | 120$^{d}$ | 141$^{c}$ | 4 |
| 2-Butanol | 0$^{b}$ | 439$^{a}$ | 499$^{a}$ | 406$^{a}$ | 445$^{a}$ | 511$^{a}$ | 74 |
| 1-Butanol | 222$^{b}$ | 269$^{a}$ | 163$^{c}$ | 225$^{b}$ | 166$^{c}$ | 193$^{bc}$ | 10 |
| 1-Pentanol | 1701$^{a}$ | 1989$^{a}$ | 834$^{b}$ | 834$^{b}$ | 576$^{b}$ | 641$^{b}$ | 113 |
| 1-Hexanol | 138$^{c}$ | 331$^{a}$ | 0$^{d}$ | 185$^{b}$ | 0$^{d}$ | 0$^{d}$ | 13 |
| ***Aldehydes*** | ***5568$^{b}$*** | ***8414$^{a}$*** | ***556$^{c}$*** | ***1917$^{c}$*** | ***671$^{c}$*** | ***2030$^{c}$*** | ***545*** |
| Acetaldehyde | 1413$^{b}$ | 2836$^{a}$ | 440$^{c}$ | 1078$^{b}$ | 501$^{c}$ | 1074$^{b}$ | 117 |
| Propanal | 0$^{b}$ | 197$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 23 |
| 3-Methyl-butanal | 160$^{b}$ | 284$^{a}$ | 0$^{c}$ | 0$^{c}$ | 169$^{b}$ | 186$^{b}$ | 28 |
| Pentanal | 419$^{b}$ | 650$^{a}$ | 0$^{d}$ | 191$^{c}$ | 0$^{d}$ | 163$^{c}$ | 43 |
| Hexanal | 3575$^{a}$ | 3955$^{a}$ | 115$^{b}$ | 375$^{b}$ | 0$^{b}$ | 288$^{b}$ | 589 |
| Heptanal | 0$^{c}$ | 489$^{a}$ | 0$^{c}$ | 271$^{b}$ | 0$^{c}$ | 318$^{b}$ | 15 |
| ***Cyclo compounds*** | ***0$^{b}$*** | ***498$^{a}$*** | ***0$^{b}$*** | ***559$^{a}$*** | ***0$^{b}$*** | ***542$^{a}$*** | ***44*** |
| Toluene | 0$^{b}$ | 498$^{a}$ | 0$^{b}$ | 559$^{a}$ | 0$^{b}$ | 542$^{a}$ | 44 |
| ***Total volatiles*** | ***22328$^{c}$*** | ***38465$^{a}$*** | ***15134$^{d}$*** | ***32369$^{b}$*** | ***15839$^{d}$*** | ***32940$^{b}$*** | ***2364*** |

$^{a-c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 8. Volatile compounds of beef added with 15% fat and different additives after 0 day storage at 4° C

| Compound | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ---------------------- (Total ion counts x $10^4$) ------------------------ | | | | | | |
| ***Hydrocarbons*** | ***8929$^{ab}$*** | ***13414$^{a}$*** | ***5767$^{b}$*** | ***13087$^{a}$*** | ***5717$^{b}$*** | ***10847$^{a}$*** | ***1224*** |
| 2-Methyl-butane | 435$^{b}$ | 333$^{b}$ | 528$^{b}$ | 565$^{b}$ | 1184$^{a}$ | 705$^{b}$ | 109 |
| Pentane | 4820$^{ab}$ | 6152$^{a}$ | 1743$^{b}$ | 3652$^{ab}$ | 1492$^{b}$ | 1484$^{b}$ | 822 |
| 1,3-Pentadiene | 0$^{b}$ | 124$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0b |
| 1-Hexene | 0$^{b}$ | 329$^{a}$ | 0$^{b}$ | 381$^{a}$ | 0$^{b}$ | 348$^{a}$ | 29 |
| Hexane | 1850$^{c}$ | 2061$^{c}$ | 3220$^{bc}$ | 4833$^{a}$ | 2741$^{c}$ | 4444$^{ab}$ | 441 |
| 1-Heptene | 0$^{b}$ | 385$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 381$^{a}$ | 18 |
| Heptane | 1139$^{a}$ | 1976$^{a}$ | 0$^{b}$ | 1946$^{a}$ | 0$^{b}$ | 1591$^{a}$ | 268 |
| Octane | 683$^{b}$ | 1664$^{a}$ | 275$^{b}$ | 1320$^{a}$ | 299$^{b}$ | 1561$^{a}$ | 185 |
| Nonane | 0$^{b}$ | 340$^{a}$ | 0$^{b}$ | 304$^{a}$ | 0$^{b}$ | 331$^{a}$ | 13 |
| | | | | | | | |
| ***Ketones*** | ***6030$^{b}$*** | ***9598$^{a}$*** | ***5721$^{b}$*** | ***10282$^{a}$*** | ***5124$^{b}$*** | ***9983a*** | ***710*** |
| 2-Propanone | 4096 | 4469 | 4188 | 4494 | 3625 | 4451 | 299 |
| 2,3-Butanedione | 738$^{b}$ | 1970$^{a}$ | 1360$^{ab}$ | 1630$^{ab}$ | 1321$^{ab}$ | 1521$^{ab}$ | 264 |
| 2-Butanone | 1194$^{b}$ | 3158$^{a}$ | 173$^{b}$ | 4157$^{a}$ | 177$^{b}$ | 4010$^{a}$ | 371 |
| | | | | | | | |
| ***Alcohols*** | ***4916*** | ***6542*** | ***3541*** | ***5981*** | ***6786*** | ***5202*** | ***15***28 |
| Ethanol | 2326 | 3597 | 2002 | 3951 | 5197 | 3716 | 1407 |
| 2-Propanol | 201 | 357 | 236 | 335 | 563 | 185 | 122 |
| 1-Propanol | 152$^{b}$ | 184$^{a}$ | 0$^{c}$ | 150$^{b}$ | 0$^{c}$ | 142$^{b}$ | 6 |
| 2-Butanol | 368 | 459 | 444 | 528 | 419 | 444 | 58 |
| 1-Butanol | 227$^{b}$ | 273$^{a}$ | 164$^{c}$ | 233$^{b}$ | 140$^{c}$ | 167$^{c}$ | 11 |
| 1-Pentanol | 1640$^{a}$ | 1671$^{a}$ | 692$^{b}$ | 781$^{b}$ | 465$^{b}$ | 546$^{b}$ | 81 |
| | | | | | | | |
| ***Aldehydes*** | ***3843$^{b}$*** | ***6258$^{a}$*** | ***161$^{c}$*** | ***2184$^{c}$*** | ***644$^{c}$*** | ***1494$^{c}$*** | ***545*** |
| Acetaldehyde | 826$^{b}$ | 2153$^{a}$ | 0$^{b}$ | 661$^{b}$ | 310$^{b}$ | 675$^{b}$ | 267 |
| Propanal | 0$^{b}$ | 197$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 7 |
| 3-Methyl-butanal | 0$^{c}$ | 229$^{b}$ | 0$^{c}$ | 319$^{a}$ | 0$^{c}$ | 222$^{b}$ | 26 |
| Hexanal | 2834$^{a}$ | 2884$^{a}$ | 161$^{b}$ | 484$^{b}$ | 170$^{b}$ | 282$^{b}$ | 291 |
| Pentenal | 180$^{b}$ | 300$^{a}$ | 0$^{c}$ | 268$^{a}$ | 0$^{c}$ | 0$^{c}$ | 26 |
| Heptanal | 0$^{d}$ | 494$^{a}$ | 0$^{d}$ | 450$^{a}$ | 164$^{c}$ | 313$^{b}$ | 33 |
| | | | | | | | |
| ***Cyclo compounds*** | ***0$^{b}$*** | ***469$^{a}$*** | ***0$^{b}$*** | ***454$^{a}$*** | ***0$^{b}$*** | ***529$^{a}$*** | ***44*** |
| Toluene | 0$^{b}$ | 468$^{a}$ | 0$^{b}$ | 454$^{a}$ | 0$^{b}$ | 529$^{a}$ | 44 |
| | | | | | | | |
| ***Total volatiles*** | ***22890$^{bc}$*** | ***34468$^{a}$*** | ***15190$^{c}$*** | ***31633$^{a}$*** | ***17961$^{c}$*** | ***27712$^{ab}$*** | ***2364*** |

$^{a-c}$ Values with different superscripts within a row are significantly different ($P$<0.05)
*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 9. Volatile compounds of beef added with 20% fat and different additives after 0 day storage at 4° C

| Compound | Cont | | A+E | | A+E+S | | SEM |
|---|---|---|---|---|---|---|---|
| | Non-IR | IR | Non-IR | IR | Non-IR | IR | |
| | ---------------------- (Total ion counts x $10^4$) ------------------------ | | | | | | |
| ***Hydrocarbons*** | ***$4883^b$*** | ***$12937^a$*** | ***$7351^b$*** | ***$13624^a$*** | ***$5900^b$*** | ***$10924^a$*** | ***860*** |
| 2-methyl-butane | 394 | 733 | 1134 | 1517 | 1193 | 966 | 269 |
| Pentane | $3173^b$ | $5283^a$ | $2408^b$ | $3333^b$ | $2359^b$ | $2126^b$ | 386 |
| 1-hexene | 0b | $333^a$ | $0^b$ | $340^a$ | $0^b$ | $338^a$ | 25 |
| Hexane | $807^b$ | $1832^b$ | $3209^a$ | $3459^a$ | $1926^{ab}$ | $3270^a$ | 421 |
| 1-Heptene | 0b | $449^a$ | $0^b$ | $450^a$ | $0^b$ | $442^a$ | 15 |
| Heptane | $123^c$ | $1980^a$ | $208^c$ | $2026^a$ | $0^c$ | $1578^b$ | 88 |
| Octane | $385^b$ | $1659^a$ | $390^b$ | $1862^a$ | $421^b$ | $1620^a$ | 101 |
| Nonane | $0^b$ | $350^a$ | $0^b$ | $370^a$ | $0^b$ | $364^a$ | 11 |
| | | | | | | | |
| ***Ketones*** | ***5784b*** | ***8635a*** | ***5869b*** | ***$10680^a$*** | ***$5416^b$*** | ***$9792^a$*** | ***671*** |
| 2-Propanone | 3682 | 3844 | 3879 | 4438 | 3535 | 3941 | 283 |
| "2,3-Butanedione" | 1899 | 2090 | 1812 | 2175 | 1684 | 2277 | 375 |
| 2-Butanone | $202^c$ | $2701^b$ | $176^c$ | $4067^a$ | $196^c$ | $3571^a$ | 183 |
| | | | | | | | |
| ***Alcohols*** | ***5645*** | ***8661*** | ***4279*** | ***7498*** | ***8099*** | ***7377*** | ***1646*** |
| Ethanol | 2870 | 5506 | 2710 | 5233 | 3470 | 5453 | 1394 |
| 2-Propanol | 312 | 441 | 282 | 473 | 771 | 510 | 165 |
| 1-Propanol | 158 | 222 | 126 | 185 | 495 | 170 | 153 |
| 2-Butanol | 381 | 470 | 423 | 464 | 2722 | 441 | 972 |
| 1-Butanol | $207^c$ | $283^a$ | $156^d$ | $248^b$ | $155^d$ | $195^c$ | 10 |
| 1-Pentanol | $1715^a$ | $1737^a$ | $580^{bc}$ | $893^b$ | $483^c$ | $605^{bc}$ | 90 |
| | | | | | | | |
| ***Aldehydes*** | ***$6102^b$*** | ***$9557^a$*** | ***$597^d$*** | ***$3010^c$*** | ***$624^d$*** | ***$2610^c$*** | ***514*** |
| Acetaldehyde | $1430^b$ | $2224^a$ | $339^b$ | $1105^b$ | $421^b$ | $1045^b$ | 256 |
| Propanal | $185^b$ | $299^a$ | $0^c$ | $0^c$ | $0^c$ | $0^c$ | 19 |
| 3-Methyl-butanal | 322 | 731 | 0 | 363 | 202 | 696 | 165 |
| Pentanal | $351^b$ | $578^a$ | $0^d$ | $211^c$ | $0^d$ | $146^c$ | 34 |
| Hexanal | $3605^b$ | $4620^a$ | $257^c$ | $693^c$ | $0^c$ | $380^c$ | 335 |
| Pentenal | $0^c$ | $369^a$ | $0^c$ | $211^b$ | $0^c$ | $0^c$ | 13 |
| Heptanal | $206^c$ | $732^a$ | $0^d$ | $426^b$ | $0^d$ | $340^{bc}$ | 54 |
| | | | | | | | |
| ***Cyclo compounds*** | ***$0^c$*** | ***$507^b$*** | ***$0^c$*** | ***$590^a$*** | ***$0^c$*** | ***$567^a$*** | ***19*** |
| Toluene | $0^c$ | $507^b$ | $0^c$ | $590^a$ | $0^c$ | $567^a$ | 19 |
| | | | | | | | |
| ***Total volatiles*** | ***$20984^c$*** | ***$38073^a$*** | ***$17756^c$*** | ***$34297^{ab}$*** | ***$19618^c$*** | ***$30224^b$*** | ***1425*** |

$^{a-c}$ Values with different superscripts within a row are significantly different (*P*<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 10. Volatile compounds of beef added with 10% fat and different additives after 3 day storage at 4° C

| Compound | Cont Non-IR | Cont IR | A+E Non-IR | A+E IR | A+E+S Non-IR | A+E+S IR | SEM |
|---|---|---|---|---|---|---|---|
| | ---------------------- (Total ion counts x $10^{4}$) ------------------------ | | | | | | |
| ***Hydrocarbons*** | ***5600$^{b}$*** | ***12036$^{a}$*** | ***4841$^{b}$*** | ***10147$^{a}$*** | ***5466$^{b}$*** | ***10009$^{a}$*** | ***1164*** |
| 2-Methyl-butane | 425 | 372 | 537 | 1117 | 1092 | 1269 | 335 |
| Pentane | 3904$^{b}$ | 5849$^{a}$ | 1122$^{c}$ | 2525$^{bc}$ | 890$^{c}$ | 2183$^{c}$ | 466 |
| 1,3-Pentdiene | 146$^{b}$ | 345$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 35 |
| 1-Hexene | 0$^{b}$ | 239$^{a}$ | 0$^{b}$ | 292$^{a}$ | 0$^{b}$ | 213$^{a}$ | 26 |
| Hexane | 679$^{b}$ | 1421$^{ab}$ | 2899$^{a}$ | 3119$^{a}$ | 3239$^{a}$ | 3317$^{a}$ | 530 |
| 1-Heptene | 0$^{c}$ | 350$^{a}$ | 0$^{c}$ | 261$^{b}$ | 0$^{c}$ | 288$^{ab}$ | 22 |
| Heptane | 140$^{b}$ | 1712$^{a}$ | 0$^{b}$ | 1432$^{a}$ | 0$^{b}$ | 1325$^{a}$ | 143 |
| Octane | 303$^{b}$ | 1400$^{a}$ | 281$^{b}$ | 1216$^{a}$ | 243$^{b}$ | 1227$^{a}$ | 77 |
| 2-Octene | 0$^{b}$ | 97$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 1 |
| Nonane | 0$^{b}$ | 247$^{a}$ | 0$^{b}$ | 182$^{a}$ | 0$^{b}$ | 183$^{a}$ | 20 |
| | | | | | | | |
| ***Ketones*** | ***5785$^{b}$*** | ***9209$^{a}$*** | ***7185$^{ab}$*** | ***8770$^{a}$*** | ***7626$^{ab}$*** | ***9602$^{a}$*** | ***671*** |
| 2-Propanone | 3376 | 4211 | 4731 | 4345 | 4090 | 4557 | 337 |
| 2,3-Butanedione | 2039 | 3202 | 1952 | 2215 | 3228 | 2674 | 308 |
| 2-Butanone | 220$^{c}$ | 1626$^{b}$ | 502$^{c}$ | 2071$^{ab}$ | 308$^{c}$ | 2369$^{a}$ | 191 |
| 2-Heptanone | 148$^{ab}$ | 169$^{a}$ | 0$^{c}$ | 139$^{b}$ | 0$^{c}$ | 0$^{c}$ | 8 |
| | | | | | | | |
| ***Alcohols*** | ***9585*** | ***11184*** | ***5462*** | ***6541*** | ***7214*** | ***5804*** | ***1582*** |
| Ethanol | 4642 | 5533 | 3203 | 3752 | 5241 | 3845 | 1423 |
| 2-Propanol | 385 | 452 | 246 | 403 | 560 | 414 | 120 |
| 1-Propanol | 304$^{a}$ | 263$^{a}$ | 130$^{b}$ | 157$^{b}$ | 116$^{b}$ | 140$^{b}$ | 22 |
| 2-Butanol | 750 | 649 | 588 | 661 | 555 | 577 | 70 |
| 1-Butanol | 356$^{b}$ | 467$^{a}$ | 247$^{c}$ | 310$^{bc}$ | 219$^{c}$ | 235$^{c}$ | 27 |
| 1-Pentanol | 2447$^{b}$ | 3408$^{a}$ | 928$^{c}$ | 1110$^{c}$ | 520$^{c}$ | 590$^{c}$ | 289 |
| 1-Hexanol | 669$^{a}$ | 409$^{b}$ | 118$^{c}$ | 146$^{c}$ | 0$^{c}$ | 0$^{c}$ | 73 |
| | | | | | | | |
| ***Aldehydes*** | ***8427$^{b}$*** | ***19331$^{a}$*** | ***279$^{b}$*** | ***1370$^{b}$*** | ***693$^{b}$*** | ***948$^{b}$*** | ***2955*** |
| Acetaldehyde | 790$^{b}$ | 1955$^{a}$ | 0$^{b}$ | 349$^{b}$ | 304$^{b}$ | 477$^{b}$ | 219 |
| Propanal | 340$^{b}$ | 820$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 161 |
| 3-methyl-butanal | 251$^{ab}$ | 554$^{a}$ | 0$^{b}$ | 0$^{b}$ | 241$^{ab}$ | 282$^{ab}$ | 88 |
| Hexanal | 6841$^{b}$ | 15563$^{a}$ | 278$^{b}$ | 717$^{b}$ | 147$^{b}$ | 188$^{b}$ | 2496 |
| Heptanal | 204$^{bc}$ | 437$^{a}$ | 0$^{c}$ | 302$^{ab}$ | 0$^{c}$ | 0$^{c}$ | 53 |
| | | | | | | | |
| ***Cyclo compounds*** | ***0$^{b}$*** | ***461$^{a}$*** | ***0$^{b}$*** | ***416$^{a}$*** | ***0$^{b}$*** | ***439$^{a}$*** | ***20*** |
| Toluene | 0$^{b}$ | 460$^{a}$ | 0$^{b}$ | 415$^{a}$ | 0$^{b}$ | 439$^{a}$ | 20 |
| | | | | | | | |
| ***Total volatiles*** | ***29396$^{b}$*** | ***52221$^{a}$*** | ***17768$^{b}$*** | ***27245$^{b}$*** | ***20998$^{b}$*** | ***26802$^{b}$*** | ***3899*** |

$^{a-c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 11. Volatile compounds of beef added with 15% fat and different additives after 3 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | (Total ion counts x $10^4$) | | | | | | |
| ***Hydrocarbons*** | ***6775$^c$*** | ***20069$^a$*** | ***3737$^c$*** | ***14920$^b$*** | ***6292$^c$*** | ***12230$^b$*** | ***1022*** |
| 2-Methyl-butane | 825$^b$ | 2145$^a$ | 755$^b$ | 826$^b$ | 996$^b$ | 1088$^b$ | 157 |
| 1-Pentene | 0$^b$ | 295$^b$ | 135$^b$ | 294$^b$ | 1637$^a$ | 274$^b$ | 105 |
| Pentane | 4600$^b$ | 8196$^a$ | 0$^c$ | 4011$^b$ | 0$^c$ | 2768$^b$ | 519 |
| 1-Hexene | 0$^c$ | 414$^a$ | 0$^c$ | 398$^a$ | 0$^c$ | 340$^b$ | 15 |
| Hexane | 932$^c$ | 3031$^b$ | 2568$^{bc}$ | 5391$^a$ | 3471$^{ab}$ | 4617$^{ab}$ | 555 |
| 1-Heptene | 0$^d$ | 510$^a$ | 0$^d$ | 362$^b$ | 0$^d$ | 300$^c$ | 12 |
| Heptane | 136$^d$ | 3005$^a$ | 0$^d$ | 2077$^b$ | 0$^d$ | 1546$^c$ | 115 |
| Octane | 280$^c$ | 2109$^a$ | 279$^c$ | 1335$^b$ | 186$^c$ | 1102$^b$ | 88 |
| Nonane | 0$^c$ | 360$^a$ | 0$^c$ | 221$^b$ | 0$^c$ | 192$^b$ | 27 |
| | | | | | | | |
| ***Ketones*** | ***6379*** | ***6881*** | ***6935*** | ***8309*** | ***6753*** | ***7639*** | ***669*** |
| 2-Propanone | 3283 | 3361 | 3971 | 4344 | 3384 | 4015 | 259 |
| 2,3-Butanedione | 2471 | 2253 | 2646 | 1918 | 3231 | 1995 | 369 |
| 2-Butanone | 204$^c$ | 1266$^b$ | 317$^c$ | 2045$^a$ | 137$^c$ | 1627$^{ab}$ | 163 |
| 2,3-Pentanedione | 419$^a$ | 0$^b$ | 0$^b$ | 0$^b$ | 0$^b$ | 0$^b$ | 56 |
| | | | | | | | |
| ***Alcohols*** | ***9082*** | ***7550*** | ***6338*** | ***5824*** | ***4443*** | ***4625*** | ***1233*** |
| Ethanol | 4047 | 3218 | 4156 | 3500 | 2941 | 3093 | 1104 |
| 2-Propanol | 229 | 244 | 380 | 280 | 423 | 316 | 97 |
| 1-Propanol | 442$^a$ | 231$^b$ | 131$^b$ | 158$^b$ | 108$^b$ | 114$^b$ | 45 |
| 2-Butanol | 487 | 458 | 477 | 537 | 370 | 423 | 48 |
| 1-Butanol | 348$^b$ | 420$^a$ | 269$^c$ | 305$^{bc}$ | 204$^d$ | 212$^d$ | 17 |
| 3-Methyl-1-butanol | 143 | 174 | 119 | 99 | 109 | 141 | 34 |
| 1-Pentanol | 2198$^a$ | 2486$^a$ | 804$^b$ | 803$^b$ | 285$^b$ | 324$^b$ | 131 |
| 1-Hexanol | 1184$^a$ | 318$^b$ | 0$^b$ | 140$^b$ | 0$^b$ | 0$^b$ | 118 |
| | | | | | | | |
| ***Aldehydes*** | ***9766$^b$*** | ***15161$^a$*** | ***537$^c$*** | ***1443$^c$*** | ***476$^c$*** | ***802$^c$*** | ***976*** |
| Acetaldehyde | 533 | 824 | 322 | 605 | 299 | 450 | 140 |
| Propanal | 296$^b$ | 955$^a$ | 0$^c$ | 0$^c$ | 0$^c$ | 0$^c$ | 65 |
| 3-Methyl-butanal | 244$^b$ | 430$^a$ | 0$^c$ | 0$^c$ | 176$^b$ | 213$^b$ | 37 |
| Pentanal | 464$^b$ | 688$^a$ | 0$^c$ | 243$^c$ | 0$^c$ | 0$^c$ | 73 |
| Hexanal | 8012$^b$ | 11922$^a$ | 251$^c$ | 593$^c$ | 0$^c$ | 137$^c$ | 881 |
| Heptanal | 215$^b$ | 341$^a$ | 0$^c$ | 0$^c$ | 0$^c$ | 0$^c$ | 21 |
| | | | | | | | |
| ***Cyclo compounds*** | ***0$^b$*** | ***380$^a$*** | ***0$^b$*** | ***313$^a$*** | ***0$^b$*** | ***264$^a$*** | ***30*** |
| Toluene | 0$^c$ | 380$^a$ | 0$^c$ | 313$^{ab}$ | 0$^c$ | 263$^b$ | 30 |
| | | | | | | | |
| ***Total volatiles*** | ***32003$^b$*** | ***50042$^a$*** | ***17548$^c$*** | ***30809$^b$*** | ***17964$^c$*** | ***25559$^b$*** | ***2063*** |

$^{a\text{-}c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 12. Volatile compounds of beef added with 20% fat and different additives after 3 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ----------------------- (Total ion counts x $10^4$) ------------------------ | | | | | | |
| ***Hydrocarbons*** | ***8985$^{c}$*** | ***22128$^{a}$*** | ***13756$^{bc}$*** | ***14925$^{bc}$*** | ***9283$^{c}$*** | ***15935$^{b}$*** | ***1516*** |
| 2-Methyl-butane | 1504$^{b}$ | 2945$^{b}$ | 5837$^{a}$ | 1322$^{b}$ | 4114$^{ab}$ | 2093$^{b}$ | 713 |
| 1-Pentene | 0$^{c}$ | 425$^{a}$ | 0$^{c}$ | 279$^{b}$ | 0$^{c}$ | 319$^{b}$ | 32 |
| Pentane | 5539$^{b}$ | 8755$^{a}$ | 2521$^{c}$ | 3190$^{bc}$ | 1297$^{c}$ | 3755$^{bc}$ | 713 |
| Propane | 0$^{b}$ | 0$^{b}$ | 137$^{a}$ | 153$^{a}$ | 0$^{b}$ | 153$^{a}$ | 6 |
| 1-Hexene | 0$^{c}$ | 512$^{a}$ | 0$^{c}$ | 378$^{b}$ | 0$^{c}$ | 452$^{ab}$ | 33 |
| Hexane | 1343$^{b}$ | 3795$^{a}$ | 4790$^{a}$ | 5202$^{a}$ | 3461$^{a}$ | 5386$^{a}$ | 569 |
| 1-Heptene | 0$^{c}$ | 463$^{a}$ | 0$^{c}$ | 368$^{b}$ | 0$^{c}$ | 375$^{b}$ | 24 |
| Heptane | 150$^{d}$ | 3007$^{a}$ | 0$^{d}$ | 2241$^{b}$ | 0$^{d}$ | 1806$^{c}$ | 143 |
| 2-Pentene | 182$^{a}$ | 110$^{a}$ | 118$^{a}$ | 107$^{a}$ | 121$^{a}$ | 0$^{b}$ | 20 |
| Octane | 266$^{c}$ | 1808$^{a}$ | 351$^{c}$ | 1435$^{b}$ | 289$^{c}$ | 1331$^{b}$ | 69 |
| Nonane | 0$^{b}$ | 306$^{a}$ | 0$^{b}$ | 246$^{a}$ | 0$^{b}$ | 261$^{a}$ | 30 |
| ***Ketones*** | ***4527$^{c}$*** | ***5947$^{bc}$*** | ***5781$^{bc}$*** | ***7708$^{ab}$*** | ***5881$^{bc}$*** | ***8322$^{a}$*** | ***563*** |
| 2-Propanone | 2900 | 3098 | 3572 | 4123 | 2931 | 4079 | 326 |
| 2,3-Butanedione | 1626$^{b}$ | 1689$^{b}$ | 1936$^{b}$ | 1723$^{b}$ | 2814$^{a}$ | 2238$^{b}$ | 188 |
| 2-Butanone | 0$^{c}$ | 1159$^{b}$ | 272$^{c}$ | 1862$^{a}$ | 135$^{c}$ | 2003$^{a}$ | 207 |
| ***Alcohols*** | ***10733*** | ***9016*** | ***6946*** | ***5967*** | ***5718*** | ***6803*** | ***1983*** |
| Ethanol | 7187 | 5716 | 5454 | 4218 | 4441 | 5185 | 1799 |
| 2-Propanol | 361 | 410 | 241 | 283 | 385 | 536 | 125 |
| 1-Propanol | 367$^{a}$ | 262$^{b}$ | 156$^{bc}$ | 173$^{bc}$ | 113$^{c}$ | 142b$^{c}$ | 30 |
| 2-Butanol | 330 | 333 | 259 | 368 | 305 | 364 | 41 |
| 1-Butanol | 289$^{ab}$ | 340$^{a}$ | 196$^{c}$ | 256$^{bc}$ | 183$^{c}$ | 220$^{c}$ | 18 |
| 1-Pentanol | 1436$^{a}$ | 1665$^{a}$ | 454$^{b}$ | 666$^{b}$ | 290$^{b}$ | 354$^{b}$ | 99 |
| 1-Hexanol | 762$^{a}$ | 287$^{b}$ | 184$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 111 |
| ***Aldehydes*** | ***4061$^{b}$*** | ***14591$^{a}$*** | ***875$^{c}$*** | ***1671$^{c}$*** | ***643$^{c}$*** | ***1139$^{c}$*** | ***737*** |
| Acetaldehyde | 492$^{b}$ | 1452$^{a}$ | 0$^{b}$ | 683$^{b}$ | 326$^{b}$ | 494$^{b}$ | 200 |
| Propanal | 162$^{b}$ | 804$^{a}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 35 |
| 3-Methyl-butanal | 392 | 1042 | 503 | 426 | 316 | 491 | 238 |
| Hexanal | 3014$^{b}$ | 10927$^{a}$ | 371$^{c}$ | 561$^{c}$ | 0$^{c}$ | 154$^{c}$ | 566 |
| Heptanal | 0$^{b}$ | 364$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 34 |
| ***Cyclo compounds*** | ***0$^{b}$*** | ***298$^{a}$*** | ***0$^{b}$*** | ***277$^{a}$*** | ***0$^{b}$*** | ***288$^{a}$*** | ***10*** |
| Toluene | 0$^{b}$ | 298$^{a}$ | 0$^{b}$ | 277$^{a}$ | 0$^{b}$ | 288$^{a}$ | 10 |
| ***Total volatiles*** | ***28306$^{b}$*** | ***51980$^{a}$*** | ***27358$^{b}$*** | ***30549$^{b}$*** | ***21525$^{b}$*** | ***32487$^{b}$*** | ***2656*** |

$^{a\text{-}c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 13. Volatile compounds of beef added with 10% fat and different additives after 7 day storage at 4° C

| Compound | Cont Non-IR | Cont IR | A+E Non-IR | A+E IR | A+E+S Non-IR | A+E+S IR | SEM |
|---|---|---|---|---|---|---|---|
| | (Total ion counts x $10^4$) | | | | | | |
| ***Hydrocarbons*** | ***6448$^{cd}$*** | ***13331$^{a}$*** | ***8526$^{bc}$*** | ***11207$^{ab}$*** | ***4024$^{d}$*** | ***10607$^{ab}$*** | **1119** |
| 2-Methyl-butane | 1473 | 1057 | 708 | 1537 | 921 | 988 | 210 |
| Pentane | 3933$^{b}$ | 7920$^{a}$ | 4094$^{b}$ | 1959$^{b}$ | 0$^{b}$ | 3469$^{b}$ | 966 |
| Hexane | 612$^{d}$ | 1730$^{c}$ | 3559$^{ab}$ | 4536$^{a}$ | 2852$^{b}$ | 3766$^{ab}$ | 350 |
| 1-Heptene | 0$^{b}$ | 259$^{a}$ | 0$^{b}$ | 263$^{a}$ | 0$^{b}$ | 225$^{a}$ | 11 |
| Heptane | 176$^{d}$ | 1384$^{b}$ | 0$^{d}$ | 1616$^{a}$ | 0$^{d}$ | 1148$^{c}$ | 73 |
| Octane | 251$^{c}$ | 839$^{b}$ | 163$^{c}$ | 1143$^{a}$ | 249$^{c}$ | 867$^{b}$ | 57 |
| Nonane | 0$^{b}$ | 140$^{a}$ | 0$^{b}$ | 151$^{a}$ | 0$^{b}$ | 141$^{a}$ | 6 |
| ***Ketones*** | ***15565*** | ***9014*** | ***20994*** | ***7255*** | ***19753*** | ***6394*** | ***3786*** |
| 2-Propanone | 3269 | 3495 | 4329 | 4246 | 3806 | 3682 | 337 |
| 2,3-Butanedione | 12079 | 5208 | 16410 | 2223 | 15766 | 2097 | 3630 |
| 2-Butanone | 216$^{bc}$ | 310$^{bc}$ | 253$^{bc}$ | 783$^{a}$ | 148$^{c}$ | 615$^{ab}$ | 104 |
| ***Alcohols*** | ***61331*** | ***11212*** | ***58820*** | ***6021*** | ***31923*** | ***4270*** | ***14769*** |
| Ethanol | 50763 | 6124 | 52503 | 3816 | 29656 | 3163 | 14254 |
| 2-Propanol | 349 | 503 | 339 | 373 | 439 | 423 | 162 |
| 1-Propanol | 1219$^{a}$ | 275$^{c}$ | 798$^{b}$ | 145$^{c}$ | 180$^{c}$ | 108$^{c}$ | 64 |
| 2-Methyl-1-propanol | 699$^{a}$ | 0$^{b}$ | 778$^{a}$ | 0$^{b}$ | 422$^{ab}$ | 0$^{b}$ | 118 |
| 1-Butanol | 563$^{b}$ | 679$^{a}$ | 449$^{c}$ | 402$^{cd}$ | 295$^{d}$ | 293$^{d}$ | 32 |
| 1-Pentanol | 907 | 101 | 1055 | 93 | 628 | 95 | 316 |
| 1-Pentanol | 2928$^{a}$ | 3050$^{a}$ | 1197$^{b}$ | 1070$^{b}$ | 182$^{c}$ | 186$^{c}$ | 174 |
| 1-Hexanol | 3901$^{a}$ | 479$^{c}$ | 1699$^{b}$ | 120$^{c}$ | 119$^{c}$ | 0$^{c}$ | 244 |
| ***Aldehydes*** | ***15464$^{b}$*** | ***32329$^{a}$*** | ***12850$^{b}$*** | ***6312$^{b}$*** | ***1582$^{b}$*** | ***996$^{b}$*** | ***5328*** |
| Acetaldehyde | 1307$^{bc}$ | 2617$^{a}$ | 1874$^{ab}$ | 908$^{bc}$ | 842$^{bc}$ | 354$^{c}$ | 354 |
| Propanal | 142$^{b}$ | 1684$^{a}$ | 273$^{b}$ | 219$^{b}$ | 0$^{b}$ | 0$^{b}$ | 178 |
| 2-Methyl-propanal | 148$^{b}$ | 208$^{a}$ | 119$^{b}$ | 234$^{a}$ | 0$^{c}$ | 252$^{a}$ | 14 |
| 3-Methyl-butanal | 460$^{b}$ | 395$^{b}$ | 2139$^{a}$ | 245$^{b}$ | 428$^{b}$ | 266$^{b}$ | 238 |
| Pentanal | 0$^{b}$ | 981$^{a}$ | 448$^{b}$ | 393$^{b}$ | 0$^{b}$ | 0$^{b}$ | 119 |
| Hexanal | 13080$^{ab}$ | 25918$^{a}$ | 7865$^{b}$ | 4168$^{b}$ | 311$^{b}$ | 122$^{b}$ | 4923 |
| Heptanal | 324$^{b}$ | 523$^{a}$ | 128bc | 141$^{bc}$ | 0$^{c}$ | 0$^{c}$ | 65 |
| ***Cyclo compounds*** | ***0$^{c}$*** | ***213$^{b}$*** | ***0$^{c}$*** | ***260$^{a}$*** | ***0$^{c}$*** | ***227$^{b}$*** | ***9*** |
| Toluene | 0$^{c}$ | 213$^{b}$ | 0$^{c}$ | 260$^{a}$ | 0$^{c}$ | 227$^{b}$ | 9 |
| ***Total volatiles*** | ***98808$^{a}$*** | ***66099$^{ab}$*** | ***101189$^{a}$*** | ***31054$^{b}$*** | ***57282$^{ab}$*** | ***22495$^{b}$*** | ***12370*** |

[a-c] Values with different superscripts within a row are significantly different ($P$<0.05)
*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E ; vitamin E, and S ; sesamol, SEM; standard error of the means (n=4).

Table 14. Volatile compounds of beef added with 15% fat and different additives after 7 day storage at 4° C

| Compound | Cont Non-IR | Cont IR | A+E Non-IR | A+E IR | A+E+S Non-IR | A+E+S IR | SEM |
|---|---|---|---|---|---|---|---|
| | ---------------------- (Total ion counts x $10^4$) ---------------------- | | | | | | |
| ***Hydrocarbons*** | ***8274***$^{bc}$ | ***14103***$^{a}$ | ***8241***$^{bc}$ | ***9417***$^{bc}$ | ***5328***$^{c}$ | ***11361***$^{ab}$ | ***1162*** |
| 2-Methyl-butane | 1009$^{ab}$ | 999$^{ab}$ | 672$^{b}$ | 759$^{b}$ | 870$^{ab}$ | 1206$^{a}$ | 103 |
| 1-Pentene | 0$^{c}$ | 276$^{a}$ | 0$^{c}$ | 155$^{b}$ | 106$^{b}$ | 244$^{a}$ | 17 |
| Pentane | 5866$^{ab}$ | 7176$^{a}$ | 3286$^{bc}$ | 1517$^{c}$ | 719$^{c}$ | 2525$^{c}$ | 899 |
| Hexane | 869$^{b}$ | 2639$^{a}$ | 4006$^{a}$ | 4165$^{a}$ | 3421$^{a}$ | 4994$^{a}$ | 575 |
| 1-Heptene | 0$^{c}$ | 373$^{a}$ | 0$^{c}$ | 321$^{b}$ | 0$^{c}$ | 312$^{b}$ | 8 |
| Heptane | 229$^{c}$ | 2189$^{a}$ | 0$^{c}$ | 2014$^{a}$ | 0$^{c}$ | 1594$^{b}$ | 64 |
| Octane | 299 | 254 | 276 | 270 | 211 | 272 | 21 |
| Nonane | 0$^{b}$ | 194$^{a}$ | 0$^{b}$ | 213$^{a}$ | 0$^{b}$ | 210$^{a}$ | 17 |
| | | | | | | | |
| ***Ketones*** | ***26332***$^{a}$ | ***6724***$^{b}$ | ***13962***$^{ab}$ | ***7282***$^{b}$ | ***22541***$^{a}$ | ***6690***$^{b}$ | ***3691*** |
| 2-Propanone | 3353 | 2885 | 3253 | 3852 | 3121 | 3656 | 318 |
| 2,3-Butanedione | 22978$^{a}$ | 3528$^{b}$ | 10558$^{ab}$ | 2648$^{b}$ | 19419$^{a}$ | 2448$^{b}$ | 3499 |
| 2-Butanone | 0$^{c}$ | 310$^{b}$ | 150$^{bc}$ | 781$^{a}$ | 0$^{c}$ | 585$^{a}$ | 73 |
| | | | | | | | |
| ***Alcohols*** | ***55259*** | ***6677*** | ***38862*** | ***5687*** | ***51737*** | ***3021*** | ***14432*** |
| Ethanol | 41572 | 3069 | 34942 | 3047 | 48446 | 1903 | 14068 |
| 2-Propanol | 292 | 245 | 322 | 336 | 324 | 362 | 71 |
| 2-Methyl-2-propanol | 113$^{d}$ | 0$^{e}$ | 171$^{a}$ | 0$^{e}$ | 146$^{c}$ | 157$^{b}$ | 2 |
| 1-Propanol | 1857$^{a}$ | 220$^{b}$ | 480$^{b}$ | 173$^{b}$ | 269$^{b}$ | 109$^{b}$ | 138 |
| 2-Methyl-1-propanol | 408$^{bc}$ | 0$^{c}$ | 504$^{b}$ | 0$^{c}$ | 926$^{a}$ | 0$^{c}$ | 106 |
| 1-Butanol | 703$^{a}$ | 520$^{b}$ | 357$^{c}$ | 415$^{bc}$ | 286$^{c}$ | 296$^{c}$ | 44 |
| 3-Methyl-1-butanol | 782 | 166 | 651 | 0 | 1037 | 0 | 311 |
| 1-Pentanol | 2906$^{a}$ | 2150$^{ab}$ | 620$^{c}$ | 1510$^{b}$ | 162$^{c}$ | 191$^{c}$ | 280 |
| 1-Hexanol | 6625$^{a}$ | 304$^{b}$ | 813$^{b}$ | 204$^{b}$ | 137$^{b}$ | 0$^{b}$ | 556 |
| | | | | | | | |
| ***Aldehydes*** | ***19920***$^{a}$ | ***19819***$^{a}$ | ***5825***$^{b}$ | ***8787***$^{ab}$ | ***2558***$^{b}$ | ***1240***$^{b}$ | ***3418*** |
| Acetaldehyde | 1571 | 1783 | 820 | 1735 | 1433 | 467 | 478 |
| Propanal | 467$^{b}$ | 1087$^{a}$ | 161$^{b}$ | 605$^{b}$ | 0$^{b}$ | 0$^{b}$ | 151 |
| 2-Methyl-propanal | 186$^{b}$ | 334$^{a}$ | 0$^{c}$ | 270$^{ab}$ | 205$^{b}$ | 341$^{a}$ | 29 |
| 3-Methyl-butanal | 1385$^{a}$ | 249$^{b}$ | 347$^{b}$ | 330$^{b}$ | 509$^{b}$ | 269$^{b}$ | 165 |
| Pentanal | 1670$^{a}$ | 1069$^{ab}$ | 268$^{b}$ | 231$^{b}$ | 0$^{b}$ | 0$^{b}$ | 266 |
| Hexanal | 14330$^{a}$ | 14819$^{a}$ | 4226$^{ab}$ | 5485$^{ab}$ | 409$^{b}$ | 162$^{b}$ | 2727 |
| Heptanal | 308$^{a}$ | 474$^{a}$ | 0$^{b}$ | 129$^{b}$ | 0$^{b}$ | 0$^{b}$ | 57 |
| | | | | | | | |
| ***Cyclo compounds*** | ***0***$^{c}$ | ***1397***$^{a}$ | ***0***$^{c}$ | ***1380***$^{a}$ | ***0***$^{c}$ | ***1166***$^{b}$ | ***48*** |
| Toluene | 0$^{c}$ | 1397$^{a}$ | 0$^{c}$ | 1380$^{a}$ | 0$^{c}$ | 1166$^{b}$ | 48 |
| | | | | | | | |
| ***Total volatiles*** | ***109784***$^{a}$ | ***48719***$^{bc}$ | ***66890***$^{abc}$ | ***32553***$^{c}$ | ***82163***$^{ab}$ | ***23477***$^{c}$ | ***12351*** |

$^{a\text{-}c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 15. Volatile compounds of beef added with 20% fat and different additives after 7 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | (Total ion counts x $10^{4}$) | | | | | | |
| ***Hydrocarbons*** | ***9178***$^{bc}$ | ***15660***$^{a}$ | ***11962***$^{ab}$ | ***12402***$^{ab}$ | ***6185***$^{c}$ | ***14041***$^{ab}$ | ***1269*** |
| 2-Methyl-butane | 1176$^{b}$ | 1474$^{b}$ | 3987$^{a}$ | 711$^{b}$ | 1070$^{b}$ | 1427$^{b}$ | 439 |
| 1-Pentene | 0$^{b}$ | 262$^{a}$ | 0$^{b}$ | 377$^{a}$ | 258$^{a}$ | 226$^{a}$ | 43 |
| Pentane | 6359$^{a}$ | 7275$^{a}$ | 3729$^{b}$ | 1888$^{bc}$ | 732$^{c}$ | 2441$^{bc}$ | 662 |
| 1-Hexene | 0$^{c}$ | 321$^{b}$ | 0$^{c}$ | 321$^{b}$ | 0$^{c}$ | 440$^{a}$ | 24 |
| Hexane | 1164$^{d}$ | 2643$^{c}$ | 3717$^{bc}$ | 4508$^{ab}$ | 3859$^{bc}$ | 5637$^{a}$ | 461 |
| 1-Heptene | 0$^{b}$ | 329$^{a}$ | 0$^{b}$ | 347$^{a}$ | 0$^{b}$ | 359$^{a}$ | 15 |
| Heptane | 202$^{c}$ | 2005$^{b}$ | 180$^{c}$ | 2376$^{a}$ | 0$^{c}$ | 1980$^{b}$ | 98 |
| Octane | 275$^{c}$ | 1166$^{b}$ | 348$^{c}$ | 1592$^{a}$ | 265$^{c}$ | 1318$^{b}$ | 54 |
| Nonane | 0$^{c}$ | 181$^{b}$ | 0$^{c}$ | 278$^{a}$ | 0$^{c}$ | 210$^{b}$ | 14 |
| | | | | | | | |
| ***Ketones*** | ***18877*** | ***7243*** | ***19448*** | ***5905*** | ***23416*** | ***7552*** | ***5292*** |
| 2-Propanone | 2811 | 3089 | 3459 | 3114 | 3228 | 3728 | 250 |
| 2,3-Butanedione | 16066 | 3793 | 15712 | 2105 | 20187 | 3106 | 5203 |
| 2-Butanone | 0$^{b}$ | 359$^{b}$ | 277$^{b}$ | 684$^{a}$ | 0$^{b}$ | 716$^{a}$ | 91 |
| | | | | | | | |
| ***Alcohols*** | ***47611*** | ***6952*** | ***56534*** | ***4484*** | ***47604*** | ***3864*** | ***12581*** |
| Ethanol | 39081 | 3323 | 50672 | 2513 | 44893 | 2634 | 12464 |
| 2-Propanol | 338 | 251 | 460 | 317 | 451 | 500 | 106 |
| 1-Propanol | 1328$^{a}$ | 350$^{c}$ | 948$^{b}$ | 172$^{c}$ | 281$^{c}$ | 129$^{c}$ | 62 |
| 2-Methyl-1-propanol | 370$^{b}$ | 0$^{c}$ | 590$^{a}$ | 0$^{c}$ | 432$^{b}$ | 0$^{c}$ | 39 |
| 1-Butanol | 490$^{a}$ | 533$^{a}$ | 383$^{b}$ | 343$^{bc}$ | 243$^{c}$ | 296bc | 29 |
| 3-Methyl-1-butanol | 703 | 93 | 880 | 0 | 716 | 112 | 242 |
| 1-Pentanol | 1864$^{a}$ | 1974$^{a}$ | 956$^{b}$ | 974$^{b}$ | 300$^{c}$ | 191$^{c}$ | 167 |
| 1-Hexanol | 3435$^{a}$ | 426$^{c}$ | 1642$^{b}$ | 162$^{c}$ | 285$^{c}$ | 0$^{c}$ | 170 |
| | | | | | | | |
| ***Aldehydes*** | ***10358***$^{b}$ | ***24944***$^{a}$ | ***13258***$^{b}$ | ***3474***$^{b}$ | ***2563***$^{b}$ | ***1529***$^{b}$ | ***3043*** |
| Acetaldehyde | 1062 | 850 | 973 | 1063 | 479 | 544 | 252 |
| Propanal | 292$^{b}$ | 1857$^{a}$ | 0$^{b}$ | 236$^{b}$ | 0$^{b}$ | 0$^{b}$ | 152 |
| 3-Methyl-butanal | 1174$^{ab}$ | 796$^{ab}$ | 1932$^{a}$ | 396$^{b}$ | 1006$^{ab}$ | 844$^{ab}$ | 335 |
| Hexanal | 7619$^{b}$ | 20655$^{a}$ | 10351$^{b}$ | 1778$^{b}$ | 1076$^{b}$ | 140$^{b}$ | 2771 |
| Heptanal | 209$^{b}$ | 785$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 54 |
| | | | | | | | |
| ***Cyclo compounds*** | ***0***$^{c}$ | ***226***$^{b}$ | ***0***$^{c}$ | ***244***$^{b}$ | ***0***$^{c}$ | ***265***$^{a}$ | ***8*** |
| Toluene | 0$^{c}$ | 226$^{b}$ | 0$^{c}$ | 244$^{ab}$ | 0$^{c}$ | 265$^{a}$ | 8 |
| | | | | | | | |
| ***Total volatiles*** | ***86024***$^{a}$ | ***55025***$^{b}$ | ***101202***$^{a}$ | ***26509***$^{c}$ | ***79767***$^{a}$ | ***27251***$^{c}$ | ***7660*** |

$^{a\text{-}c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 16. Volatile compounds of beef added with 10% fat and different additives after 14 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ---------------------- (Total ion counts x $10^4$) ---------------------- | | | | | | |
| ***Hydrocarbons*** | ***12581$^{ab}$*** | ***14999$^{a}$*** | ***9053$^{b}$*** | ***14734$^{a}$*** | ***10513$^{ab}$*** | ***12653$^{ab}$*** | ***1075*** |
| 2-Methyl-butane | 1917 | 1917 | 2162 | 2050 | 2721 | 1943 | 363 |
| Pentane | 8183$^{a}$ | 8012$^{a}$ | 3144$^{b}$ | 4914$^{b}$ | 3465$^{b}$ | 2399$^{b}$ | 724 |
| 1-Hexene | 0$^{c}$ | 186$^{b}$ | 0$^{c}$ | 212$^{b}$ | 0$^{c}$ | 295$^{a}$ | 17 |
| Hexane | 1078$^{c}$ | 1720$^{c}$ | 3007$^{b}$ | 4377$^{ab}$ | 3816$^{ab}$ | 4843$^{a}$ | 402 |
| 1-Heptene | 0$^{b}$ | 258$^{a}$ | 0$^{b}$ | 255$^{a}$ | 0$^{b}$ | 273$^{a}$ | 16 |
| Heptane | 761$^{b}$ | 1672$^{a}$ | 331$^{c}$ | 1700$^{a}$ | 203$^{c}$ | 1547$^{a}$ | 95 |
| Octane | 640$^{b}$ | 1064$^{a}$ | 407$^{c}$ | 1077$^{a}$ | 306$^{c}$ | 1148$^{a}$ | 72 |
| Nonane | 0$^{c}$ | 166$^{ab}$ | 0$^{c}$ | 145$^{b}$ | 0$^{c}$ | 202$^{a}$ | 14 |
| | | | | | | | |
| ***Ketones*** | ***39087*** | ***10978*** | ***33349*** | ***9388*** | ***45151*** | ***8672*** | ***12471*** |
| 2-Propanone | 4930 | 3638 | 5641 | 4494 | 4771 | 4485 | 533 |
| 2,3-Butanedione | 33630 | 7242 | 26910 | 4592 | 39958 | 3946 | 12222 |
| 2-Butanone | 371$^{b}$ | 0$^{c}$ | 689$^{a}$ | 202$^{b}$ | 330$^{b}$ | 240$^{b}$ | 65 |
| 2-Heptanone | 154$^{a}$ | 97$^{b}$ | 108$^{b}$ | 98$^{b}$ | 90$^{b}$ | 0$^{c}$ | 11 |
| | | | | | | | |
| ***Alcohols*** | ***125396*** | ***11959*** | ***117342*** | ***14653*** | ***154207*** | ***6431*** | ***35757*** |
| Ethanol | 103125 | 5776 | 100772 | 10475 | 136568 | 4964 | 32496 |
| 2-Propanol | 641 | 322 | 860 | 313 | 656 | 451 | 150 |
| 1-Propanol | 1867$^{a}$ | 357$^{c}$ | 1110$^{b}$ | 281$^{c}$ | 1463$^{ab}$ | 134$^{c}$ | 202 |
| 2-Methyl-1-propanol | 2190 | 0 | 2201 | 0 | 3006 | 0 | 1022 |
| 1-Butanol | 776$^{ab}$ | 1001$^{a}$ | 477$^{b}$ | 793$^{ab}$ | 582$^{b}$ | 489$^{b}$ | 104 |
| 3-Methyl-1-butanol | 5468 | 99 | 7300 | 160 | 6922 | 133 | 2248 |
| 1-Pentanol | 3033$^{ab}$ | 3612$^{a}$ | 1359$^{bc}$ | 2156$^{abc}$ | 1424$^{bc}$ | 257$^{c}$ | 491 |
| 1-Hexanol | 8292$^{a}$ | 789$^{bc}$ | 3261$^{b}$ | 471$^{bc}$ | 3583$^{b}$ | 0$^{c}$ | 804 |
| | | | | | | | |
| ***Aldehydes*** | ***12706$^{b}$*** | ***48224$^{a}$*** | ***8366$^{b}$*** | ***17476$^{b}$*** | ***15695$^{b}$*** | ***868$^{b}$*** | ***4657*** |
| Acetaldehyde | 3255 | 3353 | 3006 | 890 | 5750 | 335 | 1485 |
| Butanal | 0$^{b}$ | 287$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0b | 7 |
| 3-Methyl-butanal | 4202 | 813 | 2573 | 612 | 3606 | 376 | 1380 |
| Hexanal | 4973$^{b}$ | 42497$^{a}$ | 2786$^{b}$ | 15719$^{b}$ | 6338$^{b}$ | 156$^{b}$ | 3995 |
| Heptanal | 275$^{b}$ | 1273$^{a}$ | 0$^{b}$ | 253$^{b}$ | 0$^{b}$ | 0$^{b}$ | 94 |
| | | | | | | | |
| ***Cyclo compounds*** | ***0$^{c}$*** | ***196$^{b}$*** | ***0$^{c}$*** | ***232$^{a}$*** | ***0$^{c}$*** | ***246$^{a}$*** | ***11*** |
| Toluene | 0$^{c}$ | 196$^{b}$ | 0$^{c}$ | 231$^{a}$ | 0$^{c}$ | 246$^{a}$ | 11 |
| | | | | | | | |
| ***Total volatiles*** | ***189771$^{ab}$*** | ***86357$^{bc}$*** | ***168110$^{ab}$*** | ***56482$^{c}$*** | ***225566$^{a}$*** | ***28871$^{c}$*** | ***29459*** |

$^{a-c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 17. Volatile compounds of beef added with 15% fat and different additives after 14 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ---------------------- (Total ion counts x $10^4$) ---------------------- | | | | | | |
| ***Hydrocarbons*** | ***$13639^{bc}$*** | ***$20059^{a}$*** | ***$12485^{bc}$*** | ***$16264^{ab}$*** | ***$10565^{c}$*** | ***$11879^{bc}$*** | ***1290*** |
| 2-Methyl-butane | 1721 | 1512 | 2960 | 2837 | 2342 | 1551 | 564 |
| Pentane | $8308^{a}$ | $9053^{a}$ | $4792^{b}$ | $4556^{b}$ | $3413^{b}$ | $2317^{b}$ | 793 |
| 1-Hexene | $0^{c}$ | $285^{a}$ | $0^{c}$ | $232^{b}$ | $0^{c}$ | $277^{a}$ | 11 |
| Hexane | $1411^{b}$ | $2768^{ab}$ | $3725^{a}$ | $4471^{a}$ | $3893^{a}$ | $4663^{a}$ | 459 |
| 1-Heptene | $0^{c}$ | $353^{a}$ | $0^{c}$ | $274^{b}$ | $0^{c}$ | $290^{b}$ | 9 |
| Heptane | $831^{d}$ | $2472^{a}$ | $235^{e}$ | $1973^{b}$ | $189^{e}$ | $1511^{c}$ | 76 |
| 1-Pentene | $535^{b}$ | $1778^{a}$ | $399^{b}$ | $439^{b}$ | $342^{b}$ | $0^{b}$ | 225 |
| Octane | $834^{d}$ | $1611^{a}$ | $374^{e}$ | $1291^{b}$ | $385^{e}$ | $1093^{c}$ | 47 |
| Nonane | $0^{c}$ | $227^{a}$ | $0^{c}$ | $192^{b}$ | $0^{c}$ | $177^{b}$ | 10 |
| ***Ketones*** | ***15324*** | ***9616*** | ***17370*** | ***7730*** | ***26302*** | ***9985*** | ***4540*** |
| 2-Propanone | 4600 | 3221 | 5348 | 3394 | 5792 | 4453 | 585 |
| 2,3-Butanedione | 10483 | 6234 | 11706 | 4181 | 20195 | 5351 | 4221 |
| 2-Butanone | $241^{ab}$ | $160^{b}$ | $315^{a}$ | $154^{b}$ | $315^{a}$ | $181^{b}$ | 32 |
| ***Alcohols*** | ***115636*** | ***17011*** | ***136097*** | ***12242*** | ***130720*** | ***22581*** | ***38466*** |
| Ethanol | 99385 | 11126 | 122112 | 8949 | 115370 | 20997 | 35637 |
| 2-Propanol | 638 | 309 | 609 | 404 | 671 | 392 | 106 |
| 1-Propanol | $1401^{a}$ | $485^{b}$ | $1373^{a}$ | $204^{b}$ | $1327^{a}$ | 152b | 207 |
| 2-Methyl-1-propanol | 2028 | 157 | 2253 | 0 | 3056 | 223 | 944 |
| 1-Butanol | $555^{bc}$ | $875^{a}$ | $482^{c}$ | $675^{b}$ | $458^{c}$ | $420^{c}$ | 48 |
| 3-Methyl-1-butanol | 4187 | 160 | 5022 | 132 | 6134 | 238 | 1636 |
| 1-Pentanol | $2020^{b}$ | $3074^{a}$ | $1195^{bc}$ | $1598^{bc}$ | $935^{c}$ | $159^{d}$ | 244 |
| 1-Hexanol | $5421^{a}$ | $825^{c}$ | $3050^{b}$ | $281^{c}$ | $2769^{b}$ | $0^{c}$ | 407 |
| ***Aldehydes*** | ***$5842^{bc}$*** | ***$26008^{a}$*** | ***$6664^{bc}$*** | ***$14900^{b}$*** | ***$6652^{bc}$*** | ***$1500^{c}$*** | ***2576*** |
| Acetaldehyde | 3494 | 2519 | 4808 | 2626 | 4341 | 886 | 1409 |
| 3-Methyl-butanal | 773 | 451 | 390 | 396 | 654 | 442 | 234 |
| Hexanal | $1444^{c}$ | $21978^{a}$ | $1465^{c}$ | $11686^{b}$ | $1657^{c}$ | $172^{c}$ | 1982 |
| Heptanal | $131^{b}$ | $1058^{a}$ | $0^{b}$ | $193^{b}$ | $0^{b}$ | $0^{b}$ | 72 |
| ***Cyclo compounds*** | ***$0^{b}$*** | ***$222^{a}$*** | ***$0^{b}$*** | ***$208^{a}$*** | ***$0^{b}$*** | ***$229^{a}$*** | ***7*** |
| Toluene | $0^{b}$ | $222^{a}$ | $0^{b}$ | $208^{a}$ | $0^{b}$ | $229^{a}$ | 7 |
| ***Total volatiles*** | ***150441*** | ***72916*** | ***172615*** | ***51344*** | ***174239*** | ***46174*** | ***36115*** |

$^{a-c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 18. Volatile compounds of beef added with 20% fat and different additives after 14 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ---------------------- (Total ion counts x $10^4$) ------------------------ | | | | | | |
| ***Hydrocarbons*** | ***18137$^{a}$*** | ***22413$^{a}$*** | ***8611$^{b}$*** | ***21345$^{a}$*** | ***8496$^{b}$*** | ***18975$^{a}$*** | ***2245*** |
| 2-Methyl-butane | 4043$^{ab}$ | 2171$^{ab}$ | 1623$^{b}$ | 2381$^{ab}$ | 1882$^{ab}$ | 4630$^{a}$ | 645 |
| 1-Pentene | 97 | 1705 | 85 | 303 | 183 | 266 | 596 |
| Pentane | 9802$^{a}$ | 8254$^{ab}$ | 2308$^{c}$ | 5368$^{abc}$ | 2043$^{c}$ | 3872$^{bc}$ | 1450 |
| 1-Hexene | 0$^{b}$ | 308$^{a}$ | 0$^{b}$ | 416$^{a}$ | 0$^{b}$ | 366$^{a}$ | 31 |
| Hexane | 1806$^{b}$ | 2920$^{b}$ | 3598$^{b}$ | 7197$^{a}$ | 4004$^{b}$ | 6060$^{a}$ | 676 |
| 1-Heptene | 0$^{c}$ | 367$^{a}$ | 210$^{b}$ | 428$^{a}$ | 0$^{c}$ | 0$^{c}$ | 26 |
| Heptane | 975$^{c}$ | 2442$^{b}$ | 0$^{d}$ | 3265$^{a}$ | 0$^{d}$ | 2346$^{b}$ | 249 |
| 1-Pentene | 505$^{b}$ | 2729$^{a}$ | 326$^{bc}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 95 |
| Octane | 909$^{c}$ | 1518$^{b}$ | 462$^{d}$ | 1986$^{a}$ | 383$^{d}$ | 1435$^{b}$ | 127 |
| Nonane | 0$^{c}$ | 205$^{b}$ | 0$^{c}$ | 285$^{a}$ | 0$^{c}$ | 207$^{b}$ | 18 |
| ***Ketones*** | ***15732*** | ***13734*** | ***24393*** | ***8621*** | ***27966*** | ***9707*** | ***7750*** |
| 2-Propanone | 5096 | 8851 | 5358 | 4188 | 6346 | 4394 | 2331 |
| 2,3-Butanedione | 10219 | 4695 | 18517 | 4270 | 21343 | 5093 | 7139 |
| 2-Butanone | 417$^{ab}$ | 188$^{b}$ | 519$^{a}$ | 163$^{b}$ | 277$^{ab}$ | 220$^{b}$ | 73 |
| ***Alcohols*** | ***106083$^{a}$*** | ***8845$^{b}$*** | ***93581$^{ab}$*** | ***24494$^{ab}$*** | ***94059$^{ab}$*** | ***36476$^{ab}$*** | ***21423*** |
| Ethanol | 93804 | 3860 | 86671 | 21228 | 85822 | 34370 | 20868 |
| 2-Propanol | 911$^{a}$ | 267$^{b}$ | 700$^{ab}$ | 357$^{b}$ | 995$^{a}$ | 415$^{b}$ | 133 |
| 2-Methyl-2-propanol | 111$^{c}$ | 0$^{d}$ | 125$^{bc}$ | 188$^{a}$ | 168$^{ab}$ | 89$^{c}$ | 16 |
| 1-Propanol | 1741$^{a}$ | 581$^{b}$ | 865$^{b}$ | 275$^{b}$ | 757$^{b}$ | 198$^{b}$ | 177 |
| 2-Methyl-1-propanol | 904 | 0 | 915 | 175 | 1050 | 314 | 256 |
| 1-Butanol | 444$^{bc}$ | 763$^{a}$ | 317$^{c}$ | 579$^{b}$ | 362$^{bc}$ | 397$^{bc}$ | 58 |
| 3-Methyl-1-butanol | 3186$^{a}$ | 176$^{b}$ | 2024$^{a}$ | 251$^{b}$ | 3127$^{a}$ | 350$^{b}$ | 455 |
| 1-Pentanol | 1383$^{b}$ | 2442$^{a}$ | 654$^{cd}$ | 1219$^{bc}$ | 646$^{cd}$ | 342$^{d}$ | 177 |
| 1-Hexanol | 3600$^{a}$ | 756$^{b}$ | 1310$^{b}$ | 223$^{b}$ | 1132$^{b}$ | 0$^{b}$ | 315 |
| ***Aldehydes*** | ***3296$^{b}$*** | ***29646$^{a}$*** | ***3145$^{b}$*** | ***4524$^{b}$*** | ***3563$^{b}$*** | ***3908$^{b}$*** | ***1231*** |
| Acetaldehyde | 1055 | 3399 | 2383 | 710 | 2382 | 1700 | 870 |
| Butanal | 0$^{b}$ | 213$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 20 |
| 3-Methyl-butanal | 767$^{ab}$ | 740$^{ab}$ | 271$^{b}$ | 508$^{ab}$ | 534$^{ab}$ | 2008$^{a}$ | 360 |
| Hexanal | 1306$^{b}$ | 23766$^{a}$ | 491$^{b}$ | 3166$^{b}$ | 647$^{b}$ | 200$^{b}$ | 1002 |
| Heptanal | 168$^{b}$ | 1528$^{a}$ | 0$^{b}$ | 141$^{b}$ | 0$^{b}$ | 0$^{b}$ | 99 |
| ***Cyclo compounds*** | ***0$^{c}$*** | ***218$^{b}$*** | ***0$^{c}$*** | ***277$^{a}$*** | ***0$^{c}$*** | ***233$^{b}$*** | ***13*** |
| Toluene | 0$^{c}$ | 218$^{b}$ | 0$^{c}$ | 277$^{a}$ | 0$^{c}$ | 233$^{b}$ | 13 |
| ***Total volatiles*** | ***143248$^{a}$*** | ***75060$^{ab}$*** | ***129731$^{ab}$*** | ***59546$^{b}$*** | ***134083$^{ab}$*** | ***69506$^{ab}$*** | ***18057*** |

$^{a-c}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

# CHAPTER 5. EFFECTS OF ASCORBIC ACID AND ANTIOXIDANTS ON COLOR, LIPID OXIDATION AND VOLATILES OF IRRADIATED GROUND BEEF WITH DIFFERENT AGING TIMES

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## Abstract

Beef rounds, aged for one, two, or three weeks after slaughtering, were ground, added with 0.05% (wt/wt) ascorbic acid + 0.01% (wt/wt) α- tocopherol or 0.05% (wt/wt) ascorbic acid + 0.01% (wt/wt) α- tocopherol + 0.01% (wt/wt) sesamol, placed on Styrofoam trays and wrapped with oxygen permeable plastic film, and treated with electron beam irradiation at 0 or 2.5 kGy. The meat samples were displayed under fluorescent light for 7 days at 4° C. Color, lipid oxidation, volatile analysis, oxidation-reduction potential (ORP) and carbon monoxide (CO) production were determined at 0, 3, and 7 days of storage. Irradiation increased lipid oxidation of ground beef regardless of their aging time and storage period. As aging time increased lipid oxidation increased. Combination of ascorbic acid and α-tocopherol was effective in slowing down lipid oxidation. Adding sesamol increased the effectiveness of ascorbate and tocopherol combination in reducing lipid oxidation especially as aging and storage time increased. The redness of beef were decreased by irradiation and adding ascorbic acid and α- tocopherol before irradiation was effective in maintaining the redness of irradiated ground beef over the storage period. Volatile sulfur compounds produced by irradiation at Day 0 disappeared over the storage period. Volatiles aldehydes and alcohol greatly increased as storage period increased. Ascorbic acid and α- tocopherol effectively reduced both S-volatiles and aldehydes. Compared with the nonirradiated 1-week-aged beef, the production of aldehydes almost tripled in 3-week-aged irradiated beef. The combination of ascorbic acid + α- tocopherol to ground beef was more effective in reducing ORP than adding sesamol. Irradiation increased CO production from all ground beef regardless of aging time or additives treatments.

Key words: ground beef, aging time, irradiation, antioxidants, meat quality

## Introduction

Irradiation is the best and most highly recommended method for pathogen control in ground beef. However, irradiation changes color, produces an off-odor, and accelerates lipid oxidation. These undesirable characteristics negatively impact consumer acceptance because consumer usually uses the appearance of meat, especially meat color, as an indicator of meat freshness. In beef, the color changes from the acceptable cherry red to unattractive brown color as a result of oxymyoglobin oxidation and the formation of metmyogobin. Sherbeck and others (1995) estimated that 2% to 20% of all products are discounted, discarded or further processed because of discoloration. Carbon monoxide, produced by irradiation, is responsible for the production of pink color in irradiated light meat such as poultry breast and pork (Nam and Ahn 2002a,b). The mechanism of irradiation-induced greenish or brownish gray color in ground beef reported by Nanke and others (1998), Kim and others (2002), and Nam and Ahn (2002b) is still not clear. However, it has been speculated that free radicals such as hydroxyl or sulfuryl radicals produced by irradiation can react with the binding sites of myglobin and form metmyoglobin and sulfmyoglobin leading to brown and green color, respectively (Giroux and others 2001).

Lipid oxidation in food is one of leading causes of quality deterioration. Irradiation of meat has significant impact on lipid oxidation of meat because meat contains 75% or more of water. Diehl (1995) reported that irradiation of aqueous systems produced hydroxyl radicals, which can initiate oxidative changes in meat. Irradiation-induced oxidative chemical changes in meat are dose-dependent (Ahn and others 1997) and the presence of oxygen significantly increases oxidative changes in meat (Merritt and others 1975). Ahn and others (1997) reported that lipid oxidation in meat as a result of irradiation a significant problem only under aerobic conditions. Aerobically packaged sausages irradiated at higher irradiation dose produced greater amounts of TBARS than those irradiated at lower doses. The TBARS of aerobic- or vacuum-packaged sausages with higher polyunsaturated fatty acids was higher than those with lower polyunsaturated fatty acids.

Off-odor volatile production is another negative effect of irradiation on meat quality (Ahn and Lee 2006). Many previous research showed that volatile sulfur compounds such as methyl mercaptan, hydrogen sulfide, bis(methylthio-)methane, sulfur dioxide, mercaptomethane, dimethyl sulfide, methyl thioacetate, dimethyl disulfide and trimethyl sulfide were the major compounds responsible for irradiation off-odor (Batzer and Doty 1955; Patterson and Stevenson 1995; Ahn and others 1995; Jo and others 1999; Fan and others 2002). However, other non-sulfur volatiles such as *cis*-3- and *trans*-6-nonenals, 2-methyl butanal, 3-methyl butanal, 1-hexene, 1-heptene, 1-octene, 1-nonene and oct-1-en-3-one were also reported to play important role in irradiation off-odor (Ahn and others 1995; Jo and others 1999; Fan and others 2002; Nam and others 2002). Volatile sulfur compounds have been shown to be produced by two different ways; direct radiolytic cleavage of the side chains of sulfur containing amino acids, methionine and cysteine, and the other way is by secondary reaction of primary sulfur compounds with surrounding compounds (Jo and Ahn 2000; Ahn 2002; Ahn and Lee 2002).

Because of increased consumer demand for natural products, natural antioxidants have been examined recently as alternative of widely used synthetic antioxidants, such as butylated hydroxyanisol (BHA) and butylated hydroxytoluene (BHT), in food processing. Vitamin E, a natural phenolic antioxidant, not only has the property of scavenging free-radical but also can stop free-radical reactions in meat (Gray and others 1996; Morrissey and others 1998). Nam and others (2003) reported that adding phenolic antioxidants to meat is effective in decreasing oxidative reaction by either of those two ways.

The objective of this study was to determine the effect of ascorbic acid and selected antioxidants on the color, lipid oxidation and off-odor volatiles of beef with different aging time.

## Materials and Methods

### Sample preparation

Twelve beef top rounds were obtained from a local packing plant 24 hr after slaughter and aged for 1, 2, or 3 weeks in a 4° C cold room. One round taken from each of 12 different animals, 4 per aging time, was treated as a replication. Each round was trimmed of any visible fat and ground separately through a 6-mm plate at first then through a 3-mm plate. Six different treatments were prepared: (1) nonirradiated control, (2) nonirradiated added with 0.05% (wt/wt) L-ascorbic acid (Fisher Scientific, Fair Lawn, NJ, USA) + 0.01% α-tocopherol

(Aldrich Chemical Co., Milwaukee, WI, USA), (3) nonirradiated added with 0.05% (wt/wt) L-ascorbic acid + 0.01% α-tocopherol + 0.01% sesamol (3,4-methylenedioxyphenol; Sigma St Louis, MO, USA). Treatments 4, 5, and 6 were the same as 1, 2, and 3, respectively, but with irradiation at 2.5 kGy. The additive treatments were applied as solution form: ascorbic acid and sesamol were dissolved in distilled water, while tocopherol was dissolved first in corn oil, and then oil emulsion was prepared using the aqueous solutions of ascorbic acid and sesamol. The same amounts of water and corn oil were added to all other treatments. Each additive was added to the ground meat and then mixed for 2 min in a bowl mixer (Model KSM 90; Kitchen Aid Inc., St Joseph, MI., USA). Ground beef patties (approximately 30 g) were made by hand, placed individually on Styrofoam trays and wrapped with clear stretch, oxygen-permeable meat film RMF-61 Hy (Borden Division, Borden Packaging and Industrial Products Inc., North Andover, MA, USA), using a single-roll overwrapper, Model 600A (Heat Sealing Equipment Manufacturing Co., Cleveland, OH, USA). Prepared patties were stored overnight at 4° C, and irradiated the next morning.

**Ionizing radiation**

Wrapped beef patties were irradiated at 0 or 2.5 kGy using a linear accelerator facility (Circe IIIR; Thomson CSF Linac, St. Aubin, France) with 10 MeV of energy and 5.6 KW of power level. The average dose rate was 68.7 KGy/min. Alanine dosimeter were placed on the top and bottom surfaces of a sample and were read using a 104 Electron Paramagnetic Resonance Instrument (Bruker Instruments Inc., Billerica, Mass., USA) to check the absorbed dose. The dose range absorbed at meat samples was 2.45 to 2.95 KGy (max/min ration was 1.20). The nonirradiated control (0 kGy) samples were exposed to ambient temperature of linear accelerator facility while others samples were irradiated. After irradiation, the irradiated and non irradiated meat samples were immediately returned to a 4° C cold room were they displayed under fluorescent light for 7 days. Color, lipid oxidation, volatile analysis, ORP and CO production were determined at 0, 3, and 7 days of storage.

**Thiobarbituric acid-reactive substances (TBARS) measurement**

Lipid oxidation was determined using a TBARS method (Ahn and others 1999). Five grams of ground beef were weighed into a 50-mL test tube and homogenized with 50 µL butylated hydroxytoluene (7.2%) and 15 mL of deionized distilled water (DDW) using a Polytron homogenizer (Type PT 10/35, Brinkman Instruments Inc., Westbury NY, USA) for 15 s at high speed. One mL of the meat homogenate was transferred to a disposable test tube (13 x 100 mm), and thiobarbituric acid/trichloroacetic acid (15 mM TBA/15% TCA, 2 mL) was added. The mixture was vortex mixed and incubated in a boiling water bath for 15 min to develop color. Then samples were cooled in the ice-water for 10 min, mixed again, and centrifuged for 15 min at 2500 x *g* at 4° C. The absorbance of the resulting supernatant solution was determined at 531 nm against a blank containing 1 mL of DDW and 2 mL of TBA/TCA solution. The amounts of TBARS were expressed as mg of malonaldehyde (MDA) per kg of meat.

**Color measurement**

The color of meat was measured on the surface of meat samples using a Labscan spectrophotometer (Hunter Associated Labs Inc., Reston, VA, USA) that had been calibrated against white and black reference tiles covered with the same film as those used for meat samples. CIE L*- (lightness), a*- (redness), and b*- (yellowness) values were obtained (AMSA 1991) using an illuminant A (light source). Area view and port size were 0.25 and 0.40 inch, respectively. An average value from 2 random locations on each side, upper and lower, of sample surface was used for statistical analysis.

**Oxidation-reduction potential (ORP)**

The method of Moiseeve and Cornforth (1999) were used in determining the change of ORP in meat. A pH/ion meter (Accumet 25, Fisher Scientific) connected to a platinum electrode filled with a 4 M-KCl solution saturated with AgCl was tightly inserted in the center of meat sample. To minimize the effect of air, the smallest possible pore was made before inserting the electrode and recording the ORP readings (mV).

**Carbon monoxide (CO)**

To measure carbon monoxide produced by irradiation, carbon monoxide (CO) gas was purchased from Aldrich (Milwaukee, WI, USA). The standard gas was analyzed using a gas chromatograph (GC, Model 6890; Hewlett Packard Co., Wilmington, DE, USA) with a flame ionization detector (FID). The method of Furuta and others (1992) was modified for the detection of carbon-related gases. Meat sample (10 g) was placed in a 24-mL glass vial, and the vials were flushed with helium gas (40 psi) for 5 s to minimize experimental errors due to air incorporation, then samples were microwaved for 10 s at full power. Ten minutes after microwave heating, the headspace gas of each sample (200 μL) was withdrawn using an airtight syringe and injected into a splitless inlet of a GC (Model 6890; Hewlett Packard Co.). A Carboxen-1006 Plot column (30 m x 0.32 mm id; Supelco, Bellefonte, PA, USA) was used. Helium was used as a carrier gas at a constant flow of 1.8 mL/min and oven conditions were set at 120 °C. A flame ionization detector (FID) equipped with a Nickel catalyst (Hewlett Packard Co.) was used for the methanization of CO and $CO_2$, and the temperatures of inlet, detector, and Nickel catalyst were 250, 280, and 375° C, respectively. Detector (FID) air, $H_2$, and make-up gas (He) flows were 350, 35, and 40 mL/min, respectively. The identification of carbon monoxide was achieved using standard gas and a GC/MS, and the area of each peak was integrated by using Chemstation software (Hewlett Packard Co.). To quantify the amount of gas released, peak areas (pA*sec) were converted to the concentration (ppm) of gas in the sample headspace (14 mL) using $CO_2$ concentration (330 ppm) in air.

**Volatile compounds**

A purge-and-trap apparatus (Solatek 72 and Concentrator 3100; Tekmar-Dohrmann, Cincinnati, OH, USA) connected to a gas chromatograph/mass spectrometer (HP 6890/HP 5973; Hewlett-Packard Co., Wilmington, DE, USA) was used to analyze volatiles produced (Ahn and others 2001). The ground meat sample (3 g) was placed in a 40-mL sample vial, and the vial was flushed with helium gas (40 psi) for 5 s. The maximum waiting time of a sample in a refrigerated (4° C) holding tray was less than 4 h to minimize oxidative changes before analysis (Ahn and others 2001). The meat sample was purged with helium gas (40 mL/min) for 14 min at 40° C. Volatiles were trapped using a Tenax-charcoal-silica column

(Tekmar-Dohrmann) and desorbed for 2 min at 225° C, focused in a cryofocusing module (-80° C), and then thermally desorbed into a capillary column for 60 s at 225° C.

An HP-624 column (8.5 m x 0.25 mm i.d., 1.4 μm nominal), an HP-1 column (60 m x 0.25 mm i.d., 0.25 μm nominal; Hewlett-Packard), and an HP-Wax column (6.5 m x 0.25 mm i.d., 0.25 μm nominal) were connected using zero dead-volume column connectors (J &W Scientific, Folsom, CA, USA). Ramped oven temperature was used to improve volatile separation. The initial oven temperature of 30° C was held for 6 min. After that, the oven temperature was increased to 60° C at 5° C/min, increased to 180° C at 20° C/min, increased to 210° C at 15° C/min, and then was held for 5 min at the temperature. Constant column pressure at 22.5 psi was maintained. The ionization potential of the mass selective detector (Model 5973; Hewlett-Packard) was 70 eV, and the scan range was 19.1 to 400 m/z. Identification of volatiles was achieved by comparing mass spectral data of samples with those of the Wiley Library (Hewlett-Packard). Standards were used to confirm the identification by the mass-selective detector. The area of each peak was integrated using the ChemStation (Hewlett-Packard), and the total peak area (pA*s x $10^4$) was reported as an indicator of volatiles generated from the sample.

**Statistical analysis**

The experiment was a complete randomized design with four replications. Data were analyzed by the procedures of generalized linear model of SAS (SAS Institute 1995). Student-Newman-Keuls' multiple-range test was used to compare the mean values of treatments. Mean values and standard error of the means (SEM) were reported. Significance was defined at $P < 0.05$. Analysis of variance (ANOVA) was used to determine the effects of aging time, irradiation, additives and storage period on lipid oxidation, color, carbon monoxide production and oxidation-reduction potential of ground beef.

## Results and Discussion

**Lipid oxidation**

Lipid oxidation was influenced by aging, irradiation, additives and storage (Table 1). Irradiation increased TBARS values of ground beef from the same aging time, but the increase was not significant in control, without additives, samples. The non-significant increase of lipid oxidation in beef by irradiation agrees with Houser and others (2003; 2005) who reported that at 1.6 and 4.5 kGy doses, TBARS values of irradiated ham and frankfurters were not significantly different from nonirradiated controls. Irradiated ground beef treated with additives, however, had significantly higher TBARS values compared by nonirradiated beef treated with the same additives in 1 week-aged beef, which can be explained by the interaction between irradiation and additives (Table 1). Aging influenced the lipid oxidation at 0 d, 3 d, and 7 d of storage where both 2 week- and 3 week-aged beef had higher TBARS values than 1 week-aged beef. The combination of ascorbic acid and α-tocopherol was effective in decreasing lipid oxidation in irradiated and nonirradiated ground beef with different aging and storage times. These antioxidant effects of ascorbic acid have been reported by several other researchers (Shivas and others 1984; Sanchez-Escalante and others 2001; Ahn and Nam 2004). Also, Nam and others (2003) showed similar antioxidant effects of ascorbic acid and α-tocopherol combination in ground beef, but with a higher ascorbic acid concentration. With only one exception, adding sesamol to the ascorbic acid and tocopherol combination did not show any significant difference in decreasing lipid oxidation when compared with the ascorbic acid and tocopherol combination itself, which was similar to the result of Nam and others (2003). That exception was in irradiated 3 week-aged beef at both 0d and 3d stored beef, where TBARS values of patties treated with the three additives, ascorbic + α-tocopherol + sesamol, were significantly lower than those treated only with ascorbic + α-tocopherol. As storage time increased, lipid oxidation increased, and irradiated beef had faster lipid oxidation rate compared by nonirradiated beef. This result agrees with Nam and others (2003) who reported similar result in ground beef stored for 1, 4 and 7 days.

**Color values**

The lightness (L* values) of ground beef was not affected by irradiation as indicated in Table 2. This finding agrees with Nam and Ahn (2003) who reported similar finding in irradiated ground beef, and Kim and others (2002) who reported no effect of irradiation on L* values in beef steaks. Aging influenced the lightness of ground beef, but changes were not consistent with aging time. This contradicted observations by Nam and Ahn (2003) who reported increased L* as the aging time of beef increased. Similarly, storage influenced L* values, but with no consistency. Treating beef patties with ascorbic acid, α-tocopherol and/or sesamol had no effect on L* values. This, to some extent, is consistent with results from Nam and Ahn (2003) who found little or inconsistent effect of these additives on L* values of irradiated ground beef. Also, L* values of upper side of beef patties were not different from those of the lower side.

Redness of beef was influenced by aging, irradiation, additives and storage (Table 3) Irradiation reduced the redness (a* value) of ground beef treated with no additives (control) at 0d and 3d storage. However, at 7 day stored irradiated beef had higher a* values than nonirradiated ones. These results at 0d and 3d were similar to those of others (Nanke and others 1999; Luchsing and others 1997; Kim and others 2002) who reported that color a* values of irradiated beef were lower than those nonirradiated controls. The results at 7 d, a higher a* values for irradiated compared with nonirradiated ground beef, agree with those of Kim and others (2002) who found that at 7 days of storage aerobically packaged irradiated beef had higher a* values than nonirradiated ones. Nam and Ahn (2003) reported that irradiation reduced a* values of ground beef throughout the whole storage period. The effects of aging on beef redness values did not agree with that of Nam and Ahn (2003). Our results showed that nonirradiated beef aged for 2 and 3 weeks had significantly higher a* values than those aged for only 1 week, and this finding was at both 0d and 7d of storage, whereas at 3d of storage there was  not significantly different. Aging, however, did not play any role in the effect of irradiation on a* values of irradiated beef. Similar to L* values, a* values did not show any difference between the upper and lower surfaces of beef patties.

At 0d, ascorbic acid + tocopherol was not effective in maintaining the redness of irradiated beef where a* values of those patties treated with ascorbic acid + tocopherol were not different from those of irradiated control samples. Visually, they had brown color similar to irradiated controls. However, at 3d and 7d of storage, ascorbic acid + tocopherol was very effective in maintaining the redness of irradiated beef where a* values were significantly higher than those without ascorbic acid. Aging was not a factor in the effect of ascorbic acid on the redness of beef. This is inconsistent with Nam and Ahn (2003) who reported that the power of ascorbic acid in maintaining the redness of irradiated beef was more distinct in long-term aged irradiated beef than in short-term ones. Adding sesamol to ascorbic acid + tocopherol did not increase a* values any further. In fact, adding sesamol, inconsistently, lowered a* values in few cases. These results confirm the results of Nam and Ahn (2003) who found that ascorbic acid is more effective in maintaining the redness of irradiated ground beef when used without adding sesamol.

Aging periods, irradiation, additives and storage times influenced the yellowness of ground beef (Table 4). In control samples, irradiation decreased the yellowness, b* values, of beef patties, regardless of aging, only at 0d of storage. However, there was no irradiation effect on b* values during the storage periods of 3d and 7d in control samples. Reported significant interaction between irradiation and storage (Table 4) explains this difference in irradiation effect on b* values. This result agrees with that of Nam and Ahn (2003) and Kim and others (2002). Ascorbic acid + tocopherol increased b* values of irradiated beef at 3d and 7d, but not at 0d, which also can be explained by the interaction between irradiation, additives and storage time. This finding is consistent with that of Nam and Ahn (2003) who found that adding ascorbic acid increased b* values of irradiated beef during storage. The effect of adding sesamol to ascorbic acid + tocopherol on b* values was inconsistent and did not show any significant trends. No significance differences were found between the upper and lower surface b* values with the exception of few and inconsistent cases in 1-week-aged beef where lower surfaces had lower b* values than upper surfaces.

**Oxidation-reduction potential**

While aging did not influence the oxidation-reduction potential of ground beef, irradiation, additives and storage periods did (Table 5). The addition of ascorbic acid + α-tocopherol was effective in lowering the ORP in irradiated ground beef regardless of the age of meat. Some of these effects, however, were not significant. Samples treated with sesamol in addition to ascorbic acid + α-tocopherol had higher ORP values than the ones treated with ascorbic acid + α-tocopherol only. Thus, the use of ascorbic acid + α-tocopherol combination was more effective in reducing ORP values than other antioxidants. The lowered ORP values by ascorbic acid maintained heme pigments in the ferrous state and stabilized the color of irradiated ground beef. Ascorbic acid accelerated metmyoglobin reduction by donating electrons to ferric state of heme (Judge and others 1989) and facilitated the conversion of ferrimyoglobin to ferrous myoglobin (Anderson and Skibsted 1992). Irradiation initially decreased ORP values only at 1-week aged meat while at 2- and 3-week aged irradiated beef had higher ORP compared with control. As the storage time increased after irradiation, ORP values of ground beef increased in all treatments. However, the ground beef added with ascorbic acid still maintained lower ORP values than irradiated controls. In nonirradiated ground beef ORP values decreased over the storage time. Generally, the ORP of raw meats declined during storage due to the oxygen consumption of meat tissues or microorganisms. Cornforth and others (1986) reported that microbial growth decreased ORP and thus increased reducing capacity. Nam and Ahn (2003) reported that addition of ascorbic acid significantly lowered the ORP values of irradiated ground beef regardless of the age of meat. The lowered ORP values by ascorbic acid maintained heme pigments in ferrous status and stabilized the color of irradiated ground beef.

**Carbon monoxide (CO) production**

CO production was influenced by aging, irradiation and storage but not by additives (Table 6). Irradiation increased the production of CO from ground beef regardless of the age of meat and the additives treatments but no CO was produced from nonirradiated beef over storage period. As storage time increased after irradiation the production of CO in irradiated meat decreased. Aging period influenced the production of CO by irradiation, but changes were not consistent with aging period. There was a significant interaction between aging and irradiation. Watts and others (1978) reported that fresh raw meat exposed to low levels of CO gas became red in color with the formation of CO-myoglobin. CO is one of the major radiolytic gases produced from foodstuffs (Simic and others 1979). Nam and Ahn (2002a) reported that the red or pink color of irradiated poultry meat was due to the production of CO by irradiation which can form CO-myoglobin.

**Volatiles production**

Production of volatile compounds in ground beef at 0d of storage was influenced by irradiation, antioxidants treatments and aging (Tables 7 to 9). Irradiation increased total volatiles production especially from 1-week-aged beef. Irradiation also generated few sulfur compounds that were not produced from nonirradiated beef such as dimethyl disulfide, ethanethioic acid S-methyl ester, and methanethiol. Newly generated or increased volatiles by irradiated included hydrocarbons such as hexane, heptane, and octane; ketones such as 2,3- butanedione, 2-butanone, and 2-heptanone; cyclo-compounds such as toluene; and alcohols such as ethanol and 1-propanol. Aldehydes were not greatly affected by irradiation at 0d storage. Adding ascorbic acid + α-tocopherol decreased the production of sulfur compounds and aldehydes in irradiated beef. Adding sesamol to ascorbic acid + α-tocopherol did not greatly affect volatiles produced from 1-week-aged irradiated beef. However, 2-week- and 3-week-aged irradiated beef treated with ascorbic acid + α-tocopherol + sesamol produced higher amounts of aldehydes and sulfur compounds, respectively, when compared to those treated with ascorbic acid + α-tocopherol. Thus, adding sesamol to the combination of ascorbic acid + α-tocopherol reduced its effectives in controlling sulfur and aldehydes compounds. Aging influenced volatiles production by irradiation, where irradiated 3-week-aged beef produced greater amounts, about 3 times more, of total aldehydes than 1- and 2-week-aged irradiated beef.

After 3 days of storage (Tables 10 to 12) the volatiles profile was different from that at 0 d. Sulfur compound totally disappeared from all irradiated beef. Total amount of produced hydrocarbons, aldehydes and alcohols were greater than those produced at 0 d. Ketones, however, were decreased with 2-propanone being the predominant ketone. The amount of total produced volatiles was not greatly different. As storage period increased to 7d (Tables 13-15), the total amount of produced volatiles of nonirradiated beef became greater than that of irradiated ones. Alcohols and a newly generated acetic acid were the main contributors to this increase with acetic acid being the highest. Hexanal were the predominant aldehydes and its amount was much greater than that at 0 d and 3 d of storage. Similar to 3 day of storage, there was no sulfur compounds produced from irradiated meat at 7d.

Ahn and others (2000) reported that S-containing volatiles were highly dependent upon irradiation dose and the off-odor in irradiated pork was produced by compounding effects of volatiles from lipid oxidation and radiolytic degradation of various amino acid side chains. S-volatiles were responsible for the characteristic off-odor in irradiated meat but readily disappears during storage under aerobic conditions because sulfur compounds are highly volatile (Ahn and others 2001). Nam and others (2003) reported that aging time of beef is important factor influencing volatile production. Lee and others (1996) reported that irradiation of pre-rigor beef followed by aging at high temperature shortened aging time without any important quality problems compared with the conventional aging method. Therefore, irradiation of beef before aging rather than after aging would be more beneficial in minimizing quality changes. Hexanal is a good indicator of lipid oxidation (Shahidi and others 1987). When irradiated beef was aerobically stored, the generation of lipid oxidation products was a bigger concern than S-volatiles, because aerobic packaging is very effective in eliminating S-volatiles (Nam and others 2003).

## Conclusion

Lipid oxidation of irradiated ground beef increased as aging period and storage times increased. Adding sesamol to the combination of ascorbic acid + α-tocopherol increased the effect of ascorbic acid + α-tocopherol in controlling lipid oxidation over the storage period. However, sesamol, occasionally, lowered the redness of beef. Aging was not a significant factor influencing the redness of irradiated beef. As aging period increased volatiles such as aldehydes increased. Therefore, irradiation of beef before aging or beef aged for very short time would be better than after aging in order to minimize quality changes.

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Table 1. TBARS values of irradiated beef with different additives, aging period, and storage times at 4° C

(Unit: mg MDA/kg meat)

| | 1-week aging | | | 2-week aging | | | 3-week aging | | |
|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | IR | SEM | Non-IR | IR | SEM | Non-IR | IR | SEM |
| ***Day 0*** | | | | | | | | | |
| Cont. | 0.55[a] | 0.69[a] | 0.10 | 1.06[a] | 1.05[a] | 0.17 | 1.20[a] | 1.35[a] | 0.10 |
| A+E | 0.19[by] | 0.24[bx] | 0.01 | 0.43[b] | 0.44[b] | 0.04 | 0.65[b] | 0.79[b] | 0.0.7 |
| A+E+S | 0.18[by] | 0.22[bx] | 0.01 | 0.35[b] | 0.40[b] | 0.03 | 0.46[b] | 0.52[c] | 0.03 |
| SEM | 0.05 | 0.06 | | 0.11 | 0.10 | | 0.06 | 0.08 | |
| ***Day 3*** | | | | | | | | | |
| Cont. | 0.89[a] | 1.58[a] | 0.31 | 1.22[a] | 1.37[a] | 0.28 | 1.36[a] | 1.65[a] | 0.14 |
| A+E | 0.20[by] | 0.41[bx] | 0.03 | 0.47[b] | 0.65[b] | 0.08 | 0.60[by] | 0.91[bx] | 0.07 |
| A+E+S | 0.20[b] | 0.22[b] | 0.01 | 0.39[b] | 0.39[b] | 0.03 | 0.46[b] | 0.47[c] | 0.03 |
| SEM | 0.13 | 0.22 | | 0.16 | 0.18 | | 0.07 | 0.11 | |
| ***Day 7*** | | | | | | | | | |
| Cont. | 1.18[a] | 3.14[a] | 0.86 | 1.41[a] | 2.08[a] | 0.36 | 1.55[a] | 2.56[a] | 0.35 |
| A+E | 0.23[by] | 0.58[bx] | 0.06 | 0.50[b] | 0.82[b] | 0.15 | 0.75[b] | 1.23[b] | 0.17 |
| A+E+S | 0.21[by] | 0.28[bx] | 0.01 | 0.40[b] | 0.48[b] | 0.03 | 0.52[b] | 0.58[b] | 0.02 |
| SEM | 0.20 | 0.67 | | 0.18 | 0.26 | | 0.10 | 0.30 | |

| | DF | F value | P |
|---|---|---|---|
| Aging (A) | 2 | 11.91 | 0.0001 |
| Irradiation (IR) | 1 | 21.61 | 0.0001 |
| Additives (AD) | 2 | 120.15 | 0.0001 |
| Storage (S) | 2 | 17.71 | 0.0001 |
| A x IR | 2 | 1.24 | 0.2916 |
| A x AD | 4 | 0.79 | 0.5361 |
| A x S | 4 | 0.69 | 0.6019 |
| IR x AD | 2 | 6.41 | 0.0021 |
| IR x S | 2 | 5.76 | 0.0038 |
| AD x S | 4 | 7.96 | 0.0001 |
| A x IR x AD | 4 | 1.24 | 0.2960 |
| A x IR x S | 4 | 0.32 | 0.8655 |
| A x AD x S | 8 | 0.82 | 0.5820 |
| IR x AD x S | 4 | 2.73 | 0.0311 |
| A x IR x AD x S | 8 | 0.33 | 0.9522 |

[a-c] Values with different letters within a column of each storage period are significantly different ($P<0.05$)

[x-y] Values with different letters within a row of each aging period are significantly different ($P<0.05$)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S ; sesamol, SEM; standard error of the means (n=4).

Table 2. CIE color L-values of irradiated beef with different additives, aging periods, and storage times at 4° C

| | 1-week aging | | | | | 2-week aging | | | | | 3-week aging | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | | IR | | | Non-IR | | IR | | | Non-IR | | IR | | |
| | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM |
| ***Day 0*** | | | | | | | | | | | | | | | |
| Cont. | 42.1 | 41.7 | 39.1 | 38.6 | 1.1 | 45.2$^{w}$ | 43.4$^{wx}$ | 41.6$^{x}$ | 41.4$^{x}$ | 0.9 | 44.3 | 42.9 | 41.8 | 40.1 | 0.9 |
| A+E | 40.9 | 41.4 | 38.3 | 39.4 | 1.4 | 43.7$^{w}$ | 43.6$^{w}$ | 40.7$^{x}$ | 39.9$^{x}$ | 0.8 | 44.4$^{w}$ | 43.9$^{w}$ | 41.9$^{wx}$ | 40.6$^{x}$ | 0.9 |
| A+E+S | 42.0 | 41.8 | 38.2 | 39.2 | 0.9 | 44.0$^{w}$ | 43.7$^{w}$ | 41.6$^{wx}$ | 39.8$^{x}$ | 0.9 | 44.8 | 43.6 | 40.9 | 40.3 | 1.4 |
| SEM | 1.1 | 1.2 | 1.2 | 1.2 | | 0.8 | 0.7 | 1.0 | 1.1 | | 1.1 | 0.9 | 1.2 | 1.0 | |
| ***Day 3*** | | | | | | | | | | | | | | | |
| Cont. | 40.7 | 41.2 | 42.1 | 42.8 | 1.5 | 42.1 | 44.2 | 44.9 | 44.4 | 1.1 | 42.8$^{x}$ | 42.5$^{x}$ | 46.3$^{w}$ | 43.9$^{x}$ | 0.8 |
| A+E | 40.4 | 42.1 | 42.6 | 41.9 | 1.3 | 43.7 | 43.4 | 44.1 | 43.3 | 0.9 | 41.5$^{x}$ | 42.1$^{wx}$ | 45.5$^{w}$ | 43.4$^{wx}$ | 1.0 |
| A+E+S | 41 | 41.5 | 40.5 | 41.6 | 1.0 | 42.7 | 43.9 | 45.3 | 43.7 | 1.5 | 42.7 | 41.9 | 45.5 | 43.2 | 1.0 |
| SEM | 1.4 | 1.0 | 1.4 | 1.2 | | 1.3 | 1.0 | 1.4 | 1.0 | | 1.0 | 1.1 | 0.8 | 0.9 | |
| ***Day 7*** | | | | | | | | | | | | | | | |
| Cont. | 43.5 | 43.8 | 41.5 | 42.6 | 1.2 | 46.2 | 45.5 | 44.1 | 44.5 | 1.0 | 45.3$^{a}$ | 44.42 | 43.6 | 43.7 | 0.7 |
| A+E | 41.9 | 41.9 | 40.8 | 41.2 | 1.3 | 43.7 | 44.8 | 44.3 | 44.2 | 0.9 | 41.8$^{b}$ | 43.3 | 43.4 | 42.9 | 0.9 |
| A+E+S | 41.5 | 42.8 | 40.9 | 41.5 | 1.1 | 45.5 | 45.5 | 43.4 | 44.2 | 0.9 | 42.1$^{b}$ | 43.5 | 42.8 | 44.6 | 0.7 |
| SEM | 1.2 | 1.1 | 1.3 | 1.2 | | 1.0 | 0.8 | 1.0 | 1.0 | | | 0.8 | 0.7 | 1.0 | 0.7 |

| | DF | F value | P | | DF | F value | P |
|---|---|---|---|---|---|---|---|
| Aging (A) | 2 | 31.63 | 0.0001 | IR x S | 2 | 23.96 | 0.0001 |
| Irradiation (IR) | 1 | 3.12 | 0.0781 | AD x S | 4 | 0.60 | 0.6620 |
| Additives (AD) | 2 | 2.44 | 0.0887 | A x IR x AD | 4 | 0.17 | 0.9517 |
| Storage (S) | 2 | 5.97 | 0.0028 | A x IR x S | 4 | 0.42 | 0.7968 |
| A x IR | 2 | 1.71 | 0.1821 | A x AD x S | 8 | 0.32 | 0.9584 |
| A x AD | 4 | 0.15 | 0.9616 | IR x AD x S | 4 | 0.64 | 0.6341 |
| A x S | 4 | 1.21 | 0.3070 | A x IR x AD x S | 8 | 0.57 | 0.8054 |
| IR x AD | 2 | 0.64 | 0.5295 | | | | |

$^{a\text{-}b}$ Values with different letters within a column of each storage period are significantly different (*P*<0.05)

$^{w\text{-}y}$ Values with different letters within a row of each aging period are significantly different (*P*<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S ; sesamol, SEM; standard error of the means (n=4).

Table 3. CIE color a-values of irradiated beef with different additives, aging periods, and storage times at 4° C

| | 1-week aging | | | | | 2-week aging | | | | | 3-week aging | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | | IR | | | Non-IR | | IR | | | Non-IR | | IR | | |
| | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM |
| ***Day 0*** | | | | | | | | | | | | | | | |
| Cont. | 21.4$^{cw}$ | 19.1$^{bx}$ | 17.0$^{y}$ | 16.8$^{y}$ | 0.6 | 24.2$^{bw}$ | 23.2$^{w}$ | 17.9$^{x}$ | 17.4$^{bx}$ | 0.6 | 25.0$^{w}$ | 23.4$^{w}$ | 17.0$^{x}$ | 16.9$^{x}$ | 0.9 |
| A+E | 25.0$^{aw}$ | 21.6$^{ax}$ | 17.1$^{y}$ | 15.8$^{y}$ | 0.7 | 27.1$^{aw}$ | 25.2$^{x}$ | 17.9$^{y}$ | 17.6$^{by}$ | 0.6 | 27.0$^{w}$ | 25.8$^{w}$ | 17.3$^{x}$ | 18.0$^{x}$ | 1.1 |
| A+E+S | 23.4$^{bw}$ | 21.4$^{ax}$ | 18.3$^{y}$ | 16.6$^{z}$ | 0.4 | 25.1$^{bw}$ | 23.4$^{x}$ | 19.3$^{y}$ | 19.2$^{ay}$ | 0.5 | 25.4$^{w}$ | 24.3$^{w}$ | 18.8$^{x}$ | 18.5$^{x}$ | 0.7 |
| SEM | 0.5 | 0.4 | 0.7 | 0.6 | | 0.5 | 0.8 | 0.4 | 0.5 | | 1.2 | 0.9 | 0.6 | 0.7 | |
| ***Day 3*** | | | | | | | | | | | | | | | |
| Cont. | 19.8$^{aw}$ | 20.3$^{aw}$ | 13.9$^{cx}$ | 12.9$^{cx}$ | 0.6 | 20.9 | 18.2 | 17.6$^{b}$ | 17.4$^{b}$ | 0.1 | 19.3$^{w}$ | 19.8$^{w}$ | 13.5$^{cx}$ | 14.5$^{cx}$ | 0.6 |
| A+E | 20.5$^{awx}$ | 19.5$^{ax}$ | 21.3$^{aw}$ | 20.5$^{awx}$ | 0.4 | 19.9$^{wx}$ | 18.4$^{x}$ | 22.1$^{aw}$ | 22.3$^{aw}$ | 0.9 | 21.1 | 21.9 | 22.2$^{a}$ | 22.9$^{a}$ | 0.6 |
| A+E+S | 18.0$^{b}$ | 17.3$^{b}$ | 18.1$^{b}$ | 17.9$^{b}$ | 0.4 | 18.1 | 16.8 | 17.8$^{b}$ | 19.0$^{b}$ | 0.7 | 18.6$^{wx}$ | 20.3$^{w}$ | 16.6$^{bx}$ | 17.9$^{bwx}$ | 0.8 |
| SEM | 0.4 | 0.5 | 0.6 | 0.4 | | 0.8 | 1.0 | 0.8 | 0.8 | | 0.7 | 0.9 | 0.4 | 0.5 | |
| ***Day 7*** | | | | | | | | | | | | | | | |
| Cont. | 11.8$^{by}$ | 12.2$^{cy}$ | 16.0$^{bw}$ | 13.7$^{bx}$ | 0.4 | 14.9$^{bx}$ | 14.3$^{x}$ | 17.5$^{cw}$ | 15.4$^{bwx}$ | 0.7 | 16.1 | 14.1 | 16.3$^{c}$ | 14.7$^{c}$ | 0.6 |
| A+E | 14.9$^{ay}$ | 16.0$^{ay}$ | 21.8$^{aw}$ | 18.9$^{ax}$ | 0.4 | 20.1$^{a}$ | 17.3 | 21.2$^{a}$ | 19.1$^{a}$ | 1.1 | 16.9$^{x}$ | 15.9$^{x}$ | 22.1$^{aw}$ | 20.7$^{aw}$ | 0.5 |
| A+E+S | 14.5$^{ay}$ | 14.5$^{by}$ | 20.4$^{aw}$ | 18.0$^{ax}$ | 0.3 | 16.3$^{abx}$ | 15.8$^{x}$ | 19.9$^{bw}$ | 18.5$^{awx}$ | 0.9 | 17.4 | 16.1 | 19.5$^{b}$ | 17.9$^{b}$ | 0.9 |
| SEM | 0.2 | 0.3 | 0.5 | 0.5 | | 1.4 | 0.9 | 0.4 | 0.5 | | 0.9 | 0.8 | 0.4 | 0.5 | |

| | DF | F value | P | | DF | F value | P |
|---|---|---|---|---|---|---|---|
| Aging (A) | 2 | 17.77 | 0.0001 | IR x S | 2 | 251.46 | 0.0001 |
| Irradiation (IR) | 1 | 72.25 | 0.0001 | AD x S | 4 | 11.35 | 0.0001 |
| Additives (AD) | 2 | 85.89 | 0.0001 | A x IR x AD | 4 | 1.89 | 0.1107 |
| Storage (S) | 2 | 128.82 | 0.0001 | A x IR x S | 4 | 3.76 | 0.0051 |
| A x IR | 2 | 9.11 | 0.0001 | A x AD x S | 8 | 1.67 | 0.1042 |
| A x AD | 4 | 1.98 | 0.0973 | IR x AD x S | 4 | 15.89 | 0.0001 |
| A x S | 4 | 2.27 | 0.0615 | A x IR x AD x S | 8 | 1.21 | 0.2925 |
| IR x AD | 2 | 12.22 | 0.0001 | | | | |

$^{a-c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)

$^{w-y}$ Values with different letters within a row of each aging period are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S ; sesamol, SEM; standard error of the means (n=4).

Table 4. CIE color b-values of irradiated beef with different additives, aging periods, and storage times at 4° C

| | 1-week aging | | | | | 2-week aging | | | | | 3-week aging | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | | IR | | | Non-IR | | IR | | | Non-IR | | IR | | |
| | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM | upper | lower | upper | lower | SEM |
| ***Day 0*** | | | | | | | | | | | | | | | |
| Cont. | 20.0$^{bw}$ | 18.0$^{x}$ | 17.0$^{x}$ | 16.4$^{x}$ | 0.6 | 21.4$^{bw}$ | 21.4$^{w}$ | 16.6$^{bx}$ | 17.0$^{bx}$ | 0.7 | 22.3$^{w}$ | 21.8$^{w}$ | 16.6$^{x}$ | 17.2$^{x}$ | 0.8 |
| A+E | 23.0$^{aw}$ | 19.3$^{x}$ | 17.4$^{y}$ | 15.9$^{y}$ | 0.6 | 24.2$^{aw}$ | 22.8$^{w}$ | 17.5$^{aby}$ | 17.0b$^{y}$ | 0.7 | 24.1$^{w}$ | 23.8$^{w}$ | 16.8$^{x}$ | 18.0$^{x}$ | 0.8 |
| A+E+S | 21.4$^{bw}$ | 19.5$^{x}$ | 18.4$^{y}$ | 16.7$^{z}$ | 0.4 | 23.1$^{aw}$ | 22.0$^{w}$ | 19.0$^{ax}$ | 19.3$^{ax}$ | 0.6 | 23.0$^{w}$ | 21.7$^{w}$ | 18.0$^{x}$ | 17.8$^{x}$ | 0.7 |
| SEM | 0.6 | 0.5 | 0.5 | 0.6 | | 0.6 | 0.9 | 0.6 | 0.5 | | 0.8 | 0.7 | 0.7 | 0.7 | |
| ***Day 3*** | | | | | | | | | | | | | | | |
| Cont. | 17.7 | 18.4 | 18.5$^{b}$ | 17.3$^{b}$ | 0.4 | 18.6 | 18.5 | 19.1 | 18.1$^{b}$ | 0.6 | 17.7 | 18.4 | 17.8$^{b}$ | 18.4$^{b}$ | 0.4 |
| A+E | 17.0$^{x}$ | 17.6$^{x}$ | 20$^{aw}$ | 19.1$^{aw}$ | 0.4 | 18.5$^{x}$ | 18.5$^{x}$ | 20.4$^{wx}$ | 20.9$^{aw}$ | 0.6 | 17.9$^{x}$ | 18.7$^{x}$ | 20.5$^{aw}$ | 21.5$^{aw}$ | 0.5 |
| A+E+S | 17.7 | 17.3 | 18.6$^{b}$ | 18.5$^{ab}$ | 0.5 | 17.6$^{x}$ | 17.4$^{x}$ | 18.4$^{wx}$ | 19.4$^{abw}$ | 0.4 | 16.7$^{x}$ | 18.4$^{wx}$ | 17.9$^{bwx}$ | 19.0$^{bw}$ | 0.5 |
| SEM | 0.5 | 0.4 | 0.4 | 0.4 | | 0.6 | 0.5 | 0.6 | 0.6 | | 0.6 | 0.4 | 0.3 | 0.5 | |
| ***Day 7*** | | | | | | | | | | | | | | | |
| Cont. | 16.8 | 14.6$^{b}$ | 17.0$^{b}$ | 15.2$^{b}$ | 0.6 | 16.9 | 16.8 | 17.5b | 16.1 | 0.5 | 17.4 | 17.6 | 17.6$^{b}$ | 16.3$^{b}$ | 0.4 |
| A+E | 15.5$^{y}$ | 17.1$^{ax}$ | 19.9$^{aw}$ | 17.4$^{ax}$ | 0.4 | 18.9 | 17.6 | 19.2$^{a}$ | 17.2 | 0.6 | 16.9$^{x}$ | 16.4$^{x}$ | 20.2$^{aw}$ | 19.0$^{aw}$ | 0.5 |
| A+E+S | 16.5$^{x}$ | 16.1$^{abx}$ | 19.2$^{aw}$ | 16.9$^{ax}$ | 0.4 | 16.9$^{x}$ | 16.7$^{x}$ | 18.9$^{aw}$ | 17.6$^{wx}$ | 0.5 | 18.1 | 16.9 | 18.6$^{b}$ | 17.6$^{b}$ | 0.6 |
| SEM | 0.4 | 0.6 | 0.4 | 0.6 | | 0.6 | 0.6 | 0.4 | 0.6 | | 0.5 | 0.6 | 0.4 | 0.5 | |

| | DF | F value | P | | DF | F value | P |
|---|---|---|---|---|---|---|---|
| Aging (A) | 2 | 6.17 | 0.0023 | IR x S | 2 | 213.93 | 0.0001 |
| Irradiation (IR) | 1 | 23.01 | 0.0001 | AD x S | 4 | 4.89 | 0.0007 |
| Additives (AD) | 2 | 21.54 | 0.0001 | A x IR x AD | 4 | 1.41 | 0.2304 |
| Storage (S) | 2 | 75.41 | 0.0001 | A x IR x S | 4 | 1.33 | 0.2597 |
| A x IR | 2 | 6.28 | 0.0021 | A x AD x S | 8 | 1.03 | 0.4092 |
| A x AD | 4 | 0.63 | 0.6380 | IR x AD x S | 4 | 9.44 | 0.0001 |
| A x S | 4 | 1.21 | 0.3070 | A x IR x AD x S | 8 | 1.19 | 0.3060 |
| IR x AD | 2 | 3.25 | 0.0397 | | | | |

$^{a\text{-}c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)

$^{w\text{-}y}$ Values with different letters within a row of each aging period are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 5. ORP values of irradiated beef with different additives, aging period, and storage times at 4° C

(Unit: mVolt)

| | 1-week aging | | | 2-week aging | | | 3-week aging | | |
|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | IR | SEM | Non-IR | IR | SEM | Non-IR | IR | SEM |
| ***Day 0*** | | | | | | | | | |
| Cont. | $67.2^{a}$ | 17.9 | 23.4 | 9.2 | 24.2 | 25.4 | $16.3^{ay}$ | $78.6^{ax}$ | 9.0 |
| A+E | $-7.7^{b}$ | -38.2 | 9.9 | -11.9 | -16.2 | 6.4 | $-36.6^{by}$ | -7.2b$^{x}$ | 5.8 |
| A+E+S | $-10.5^{b}$ | -3.8 | 10.5 | -9.5 | -11.6 | 7.0 | $-15.3^{b}$ | $-5.1^{b}$ | 5.0 |
| SEM | 9.56 | 20.3 | | 10.4 | 19.5 | | 7.74 | 5.7 | |
| ***Day 3*** | | | | | | | | | |
| Cont. | $0.5^{ay}$ | $85.9^{ax}$ | 13.8 | $-11.6^{y}$ | $68.7^{x}$ | 14.8 | $-50.0^{y}$ | $112.0^{ax}$ | 19.4 |
| A+E | $-58.2^{by}$ | $9.0^{bx}$ | 8.7 | $-40.2^{y}$ | $32.0^{x}$ | 12.4 | $-62.6^{y}$ | $45.7^{cx}$ | 24.9 |
| A+E+S | $-52.8^{by}$ | $25.6^{bx}$ | 11.2 | $-22.8^{y}$ | $59.0^{x}$ | 12.2 | $-25.8^{y}$ | $79.0^{bx}$ | 17.3 |
| SEM | 14.4 | 7.3 | | 12.3 | 14.0 | | 27.9 | 9.2 | |
| ***Day 7*** | | | | | | | | | |
| Cont. | $-85.7^{y}$ | $125.1^{ax}$ | 22.9 | $-105.3^{y}$ | $111.8^{ax}$ | 30.6 | $-109.5^{y}$ | $91.1^{ax}$ | 8.1 |
| A+E | $-63.3^{y}$ | $86.1^{bx}$ | 12.0 | $-86.9^{y}$ | $54.7^{bx}$ | 20.7 | $-123.4^{y}$ | $49.2^{bx}$ | 21.3 |
| A+E+S | $-122.8^{y}$ | $87.6^{bx}$ | 24.5 | $-115.8^{y}$ | $39.3^{bx}$ | 26. 6 | $-108.9^{y}$ | $48.8^{bx}$ | 19.4 |
| SEM | 28.4 | 6.42 | | 35.8 | 9.9 | | 22.9 | 8.6 | |

| | DF | F value | Pr |
|---|---|---|---|
| Aging (A) | 2 | 0.5 | 0.6054 |
| Irradiation (IR) | 1 | 384.48 | 0.0001 |
| Additives (AD) | 2 | 28.12 | 0.0001 |
| Storage (S) | 2 | 8.44 | 0.0003 |
| A x IR | 2 | 4.39 | 0.0139 |
| A x AD | 4 | 1.24 | 0.2964 |
| A x S | 4 | 2.95 | 0.0219 |
| IR x AD | 2 | 3.70 | 0.0268 |
| IR x S | 2 | 115.52 | 0.0001 |
| AD x S | 4 | 2.82 | 0.0270 |
| A x IR x AD | 4 | 1.53 | 0.1946 |
| A x IR x S | 4 | 2.06 | 0.0884 |
| A x AD x S | 8 | 0.85 | 0.5613 |
| IR x AD x S | 4 | 0.66 | 0.6208 |
| A x IR x AD x S | 8 | 0.52 | 0.8371 |

$^{a-c}$ Values with different letters within a column of each storage period are significantly different ($P$<0.05)
$^{x-y}$ Values with different letters within a row of each aging period are significantly different ($P$<0.05)
*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 6. Carbon monoxide (CO) formation from irradiated beef with different additives, aging period, and storage times at 4° C

(Unit: mVolt)

| | 1-week aging | | | 2-week aging | | | 3-week aging | | |
|---|---|---|---|---|---|---|---|---|---|
| | Non-IR | IR | SEM | Non-IR | IR | SEM | Non-IR | IR | SEM |
| ***Day 0*** | | | | | | | | | |
| Cont. | 31.96$^{y}$ | 69.43$^{x}$ | 8.45 | 26.96$^{y}$ | 64.89$^{x}$ | 2.94 | 20.31$^{y}$ | 86.91$^{x}$ | 6.49 |
| A+E | 6.33$^{y}$ | 70.25$^{x}$ | 12.19 | 19.37$^{y}$ | 71.60$^{x}$ | 8.54 | 14.31$^{y}$ | 78.98$^{x}$ | 9.63 |
| A+E+S | 5.99$^{y}$ | 62.27$^{x}$ | 6.77 | 24.53$^{y}$ | 66.78$^{x}$ | 12.15 | 26.60$^{y}$ | 84.06$^{x}$ | 10.03 |
| SEM | 8.00 | 10.64 | | 11.83 | 3.59 | | 8.91 | 8.81 | |
| ***Day 3*** | | | | | | | | | |
| Cont. | 0.00$^{y}$ | 37.39$^{x}$ | 8.03 | 0.00y | 34.55$^{x}$ | 3.15 | 0.00$^{y}$ | 40.93$^{x}$ | 3.59 |
| A+E | 0.00$^{y}$ | 30.91$^{x}$ | 4.43 | 0.00y | 36.66$^{x}$ | 2.83 | 0.00$^{y}$ | 43.94$^{x}$ | 1.52 |
| A+E+S | 0.00$^{y}$ | 35.33$^{x}$ | 4.14 | 0.00y | 33.37$^{x}$ | 1.16 | 0.00$^{y}$ | 45.53$^{x}$ | 2.16 |
| SEM | 0.00 | 8.21 | | 0.00 | 3.58 | | 0.00 | 3.64 | |
| ***Day 7*** | | | | | | | | | |
| Cont. | 0.00$^{y}$ | 19.23$^{x}$ | 6.90 | 0.00y | 23.50$^{x}$ | 4.34 | 0.00$^{y}$ | 22.16$^{x}$ | 2.79 |
| A+E | 0.00$^{y}$ | 25.13$^{x}$ | 3.62 | 0.00y | 21.03$^{x}$ | 1.49 | 0.00$^{y}$ | 37.70$^{x}$ | 8.56 |
| A+E+S | 0.00$^{y}$ | 17.3$^{x}$ | 1.21 | 0.00y | 8.82$^{x}$ | 3.63 | 0.00$^{y}$ | 23.39$^{x}$ | 4.36 |
| SEM | 0.00 | 6.44 | | 0.00 | 4.78 | | 0.00 | 8.17 | |

| | DF | F value | Pr |
|---|---|---|---|
| Aging (A) | 2 | 5.12 | 0.0070 |
| Irradiation (IR) | 1 | 483.20 | 0.0001 |
| Additives (AD) | 2 | 0.69 | 0.5041 |
| Storage (S) | 2 | 155.43 | 0.0001 |
| A x IR | 2 | 4.67 | 0.0107 |
| A x AD | 4 | 0.64 | 0.6374 |
| A x S | 4 | 0.66 | 0.6172 |
| IR x AD | 2 | 1.49 | 0.2278 |
| IR x S | 2 | 27.65 | 0.0001 |
| AD x S | 4 | 1.19 | 0.3180 |
| A x IR x AD | 4 | 0.19 | 0.9419 |
| A x IR x S | 4 | 0.33 | 0.8556 |
| A x AD x S | 8 | 0.67 | 0.7187 |
| IR x AD x S | 4 | 0.70 | 0.5954 |
| A x IR x AD x S | 8 | 0.56 | 0.8120 |

$^{a\text{-}c}$ Values with different letters within a column of each storage period are significantly different (*P*<0.05)
$^{x\text{-}y}$ Values with different letters within a row of each aging period are significantly different (*P*<0.05)
*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 7. Volatiles of 1-week-aged beef with different additives after 0 day storage at 4° C

| Compound | Cont | | A+E | | A+E+S | | SEM |
|---|---|---|---|---|---|---|---|
| | Non-IR | IR | Non-IR | IR | Non-IR | IR | |
| | ---------------------- (Total ion counts x $10^{4}$) ------------------------ | | | | | | |
| ***Hydrocarbons*** | ***3705*** | ***3629*** | ***3008*** | ***3457*** | ***3293*** | ***2674*** | ***493*** |
| 2-Methyl-butane | 2192 | 1634 | 1850 | 2175 | 2220 | 2213 | 408 |
| Pentane | $1512^{a}$ | $1504^{a}$ | $608^{b}$ | $547^{b}$ | $757^{ab}$ | $0^{b}$ | 221 |
| Hexane | $0^{c}$ | $157^{b}$ | $448^{a}$ | $468^{a}$ | $314^{a}$ | $350^{a}$ | 47 |
| Heptane | $0^{b}$ | $174^{a}$ | $0^{b}$ | $147^{a}$ | $0^{b}$ | $0^{b}$ | 12 |
| Octane | $0^{c}$ | $158^{a}$ | $100^{b}$ | $118^{b}$ | $0^{c}$ | $111^{b}$ | 7 |
| | | | | | | | |
| ***Ketones*** | ***5866*** | ***9873*** | ***5239*** | ***9180*** | ***5432*** | ***8551*** | ***1305*** |
| 2-Propanone | 5866 | 7638 | 5055 | 6792 | 5277 | 6366 | 1033 |
| 2,3-Butanedione | $0^{b}$ | $187^{a}$ | $183^{a}$ | $0^{b}$ | $155^{a}$ | $0^{b}$ | 10 |
| 2-Butanone | $0^{b}$ | $1910^{a}$ | $0^{b}$ | $2387^{a}$ | $0^{b}$ | $2184^{a}$ | 437 |
| 2-Heptanone | $0^{b}$ | $135^{a}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | 1 |
| | | | | | | | |
| ***Alcohols*** | ***$2436^{b}$*** | ***$3991^{a}$*** | ***$2285^{b}$*** | ***$3856^{a}$*** | ***$1960^{b}$*** | ***$3837^{a}$*** | ***285*** |
| Ethanol | $1413^{b}$ | $2882^{a}$ | $1855^{b}$ | $3513^{a}$ | $1761^{b}$ | $3461^{a}$ | 275 |
| 1-Propanol | $118^{b}$ | $124^{a}$ | $0^{c}$ | $0^{c}$ | $0^{c}$ | $0^{c}$ | 1 |
| 2-Butanol | 366 | 300 | 301 | 210 | 198 | 243 | 43 |
| 2-methyl-2 butanol | $0^{b}$ | $198^{a}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | 16 |
| 1-Butanol | $167^{a}$ | $154^{a}$ | $128^{a}$ | $132^{a}$ | $0^{b}$ | $132^{a}$ | 10 |
| 1-Pentanol | $371^{a}$ | $330^{a}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | 32 |
| | | | | | | | |
| ***Aldehydes*** | ***$394^{a}$*** | ***$410^{a}$*** | ***$345^{a}$*** | ***$0^{b}$*** | ***$0^{b}$*** | ***$0^{b}$*** | ***45*** |
| Acetaldehyde | $394^{a}$ | $410^{a}$ | $345^{a}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | 45 |
| | | | | | | | |
| ***Sulfur compounds*** | ***$0^{b}$*** | ***$1650^{a}$*** | ***$0^{b}$*** | ***$523^{ab}$*** | ***$0^{b}$*** | ***$443^{ab}$*** | ***342*** |
| Ethanethioic- -acid--S-methyl | $0^{c}$ | $269^{a}$ | $0^{c}$ | $173^{b}$ | $0^{c}$ | $150^{b}$ | 27 |
| Dimethyl disulfide | $0^{c}$ | $1380^{a}$ | $0^{c}$ | $349^{b}$ | $0^{c}$ | $293^{b}$ | 317 |
| | | | | | | | |
| ***Cyclo compounds*** | ***$134^{b}$*** | ***$230^{a}$*** | ***$0^{c}$*** | ***$182^{b}$*** | ***$0^{c}$*** | ***$171^{b}$*** | ***16*** |
| Toluene | $0^{c}$ | $230^{a}$ | $0^{c}$ | $181^{b}$ | $0^{c}$ | $171^{b}$ | 11 |
| Benzene | $134^{a}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | 10 |
| | | | | | | | |
| ***Total volatiles*** | ***$12536^{bc}$*** | ***$19783^{a}$*** | ***$10877^{c}$*** | ***$17196^{a}$*** | ***$10684^{c}$*** | ***$15676^{abc}$*** | ***1431*** |

[a-c] Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 8. Volatiles of 2-week-aged beef with different additives after 0 day storage at 4° C

| Compound | Cont | | A+E | | A+E+S | | SEM |
|---|---|---|---|---|---|---|---|
| | Non-IR | IR | Non-IR | IR | Non-IR | IR | |
| | ------------------------- (Total ion counts x $10^4$) ------------------------- | | | | | | |
| ***Hydrocarbons*** | ***15932*** | ***19568*** | ***14608*** | ***20193*** | ***13680*** | ***20317*** | ***2423*** |
| 2-Methyl-butane | 2810 | 2926 | 2560 | 2313 | 1533 | 2769 | 366 |
| Pentane | 1254$^{a}$ | 1274$^{a}$ | 590$^{ab}$ | 850$^{ab}$ | 407$^{b}$ | 914$^{ab}$ | 189 |
| Hexane | 0$^{e}$ | 171$^{d}$ | 277$^{cd}$ | 430$^{ab}$ | 315$^{bc}$ | 524$^{a}$ | 39 |
| Heptane | 0$^{b}$ | 142$^{a}$ | 0$^{b}$ | 142$^{a}$ | 0$^{b}$ | 163$^{a}$ | 9 |
| 1-Penten | 208$^{a}$ | 196$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 22 |
| Octane | 198$^{b}$ | 301$^{ab}$ | 240$^{b}$ | 372$^{ab}$ | 315$^{ab}$ | 444$^{a}$ | 42 |
| ***Ketones*** | ***5730*** | ***7278*** | ***5470*** | ***8042*** | ***5554*** | ***7750*** | ***1069*** |
| 2-Propanone | 5605 | 6247 | 5470 | 6462 | 5553 | 6359 | 1070 |
| 2-Butanone | 125$^{c}$ | 1030$^{b}$ | 0$^{c}$ | 1579$^{a}$ | 0$^{c}$ | 1391$^{ab}$ | 141 |
| ***Alcohols*** | ***3076$^{b}$*** | ***3998$^{a}$*** | ***2466$^{c}$*** | ***3813$^{a}$*** | ***2202$^{c}$*** | ***3450$^{ab}$*** | ***180*** |
| Ethanol | 1951$^{b}$ | 2939$^{a}$ | 1626$^{b}$ | 2855$^{a}$ | 1571$^{b}$ | 2835$^{a}$ | 167 |
| 2-Propanol | 310$^{ab}$ | 343$^{ab}$ | 188$^{b}$ | 359$^{ab}$ | 427$^{a}$ | 436$^{a}$ | 51 |
| 2-Butanol | 201$^{a}$ | 171$^{a}$ | 254$^{a}$ | 223$^{a}$ | 0$^{b}$ | 0$^{b}$ | 29 |
| 1-Butanol | 186 | 189 | 200 | 182 | 204 | 178 | 21 |
| 1-Pentanol | 426$^{a}$ | 354$^{ab}$ | 198$^{b}$ | 191$^{b}$ | 0$^{c}$ | 0$^{c}$ | 46 |
| ***Aldehydes*** | ***227$^{b}$*** | ***283$^{b}$*** | ***282$^{b}$*** | ***271$^{b}$*** | ***423$^{b}$*** | ***687$^{a}$*** | ***63*** |
| Acetaldehyde | 227 | 282 | 282 | 271 | 422 | 434 | 62 |
| Heptanal | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 252$^{a}$ | 0.3 |
| ***Sulfur compounds*** | ***0$^{c}$*** | ***776$^{a}$*** | ***0$^{c}$*** | ***704$^{a}$*** | ***0$^{c}$*** | ***453$^{b}$*** | ***73*** |
| Ethanethioic--acid-S-methyl | 0$^{b}$ | 242$^{a}$ | 0$^{b}$ | 223$^{a}$ | 0$^{b}$ | 165$^{a}$ | 25 |
| Dimethyl disulfide | 0$^{c}$ | 533$^{a}$ | 0$^{c}$ | 481$^{a}$ | 0$^{c}$ | 287$^{b}$ | 62 |
| ***Cyclo compounds*** | ***186$^{a}$*** | ***168$^{a}$*** | ***206$^{a}$*** | ***191$^{a}$*** | ***0$^{b}$*** | ***167$^{a}$*** | ***21*** |
| Toluene | 0$^{b}$ | 167$^{a}$ | 0$^{b}$ | 191$^{a}$ | 0$^{b}$ | 166$^{a}$ | 18 |
| Benzene | 185$^{a}$ | 0$^{b}$ | 206$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 9 |
| ***Total volatiles*** | ***13691$^{ab}$*** | ***17515$^{a}$*** | ***12093$^{ab}$*** | ***17130$^{a}$*** | ***10751$^{b}$*** | ***17324$^{a}$*** | ***1498*** |

$^{a\text{-}c}$ Values with different superscripts within a row are significantly different ($P$<0.05)
*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 9. Volatiles of 3-week-aged beef with different additives after 0 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ------------------------- (Total ion counts x $10^4$) ------------------------- | | | | | | |
| ***Hydrocarbons*** | ***5027***$^{ab}$ | ***5664***$^{a}$ | ***3694***$^{c}$ | ***4062***$^{bc}$ | ***804***$^{d}$ | ***903***$^{d}$ | ***343*** |
| 2-Methyl-butane | 2692$^{a}$ | 2797$^{a}$ | 2946$^{a}$ | 2700$^{a}$ | 117$^{b}$ | 114$^{b}$ | 290 |
| Pentane | 1436$^{a}$ | 1590$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 100 |
| Hexane | 140$^{c}$ | 200$^{bc}$ | 192$^{bc}$ | 386$^{a}$ | 254$^{b}$ | 356$^{a}$ | 19 |
| 2,3-Butanedione | 0$^{b}$ | 178$^{a}$ | 179$^{a}$ | 261$^{a}$ | 0$^{b}$ | 0$^{b}$ | 25 |
| Heptane | 0$^{b}$ | 196$^{a}$ | 0$^{b}$ | 227$^{a}$ | 0$^{b}$ | 0$^{b}$ | 27 |
| 1-Penten | 472$^{a}$ | 367$^{ab}$ | 189$^{bc}$ | 197$^{bc}$ | 132$^{c}$ | 142$^{c}$ | 52 |
| Octane | 286 | 333 | 186 | 288 | 299 | 290 | 53 |
| | | | | | | | |
| ***Ketones*** | ***6304*** | ***7531*** | ***7040*** | ***8494*** | ***6602*** | ***9201*** | ***1600*** |
| 2-Propanone | 6304 | 6402 | 6896 | 6818 | 6601 | 7442 | 1442 |
| 2-Butanone | 0$^{b}$ | 1128$^{a}$ | 144$^{b}$ | 1675$^{a}$ | 0$^{b}$ | 1758$^{a}$ | 278 |
| | | | | | | | |
| ***Alcohols*** | ***2869***$^{b}$ | ***4546***$^{a}$ | ***2946***$^{b}$ | ***4328***$^{a}$ | ***2593***$^{b}$ | ***4123***$^{a}$ | ***151*** |
| Ethanol | 1865$^{b}$ | 3411$^{a}$ | 1992$^{b}$ | 3352$^{a}$ | 1787$^{b}$ | 3255$^{a}$ | 169 |
| 1-Propanol | 297 | 435 | 387 | 434 | 336 | 412 | 54 |
| 2-Butanol | 159 | 149 | 176 | 139 | 139 | 148 | 9 |
| 1-Butanol | 164 | 185 | 172 | 178 | 191 | 172 | 25 |
| 1-Pentanol | 383$^{a}$ | 363$^{a}$ | 217$^{b}$ | 224$^{b}$ | 138$^{b}$ | 135$^{b}$ | 25 |
| | | | | | | | |
| ***Aldehydes*** | ***938***$^{ab}$ | ***1175***$^{a}$ | ***407***$^{b}$ | ***409***$^{b}$ | ***356***$^{b}$ | ***529***$^{b}$ | ***160*** |
| Acetaldehyde | 735 | 993 | 407 | 409 | 355 | 528 | 160 |
| Hexanal | 202$^{a}$ | 181$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 24 |
| Heptanal | 0$^{c}$ | 189$^{a}$ | 0$^{c}$ | 0$^{c}$ | 142$^{b}$ | 0$^{c}$ | 1 |
| | | | | | | | |
| ***Sulfur compounds*** | ***0***$^{d}$ | ***401***$^{b}$ | ***0***$^{d}$ | ***192***$^{c}$ | ***0***$^{d}$ | ***842***$^{a}$ | ***40*** |
| Methanethiol | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 272$^{a}$ | 6 |
| Dimethyl disulfide | 0$^{d}$ | 401$^{b}$ | 0$^{d}$ | 192$^{c}$ | 0$^{d}$ | 571$^{a}$ | 40 |
| | | | | | | | |
| ***Cyclo compounds*** | ***0***$^{b}$ | ***165***$^{a}$ | ***0***$^{b}$ | ***170***$^{a}$ | ***0***$^{b}$ | ***221***$^{a}$ | ***18*** |
| Toluene | 0$^{b}$ | 165$^{a}$ | 0$^{b}$ | 170$^{a}$ | 0$^{b}$ | 221$^{a}$ | 18 |
| | | | | | | | |
| ***Total volatiles*** | ***15139***$^{ab}$ | ***19671***$^{a}$ | ***14087***$^{ab}$ | ***17656***$^{ab}$ | ***10497***$^{b}$ | ***15819***$^{ab}$ | ***1926*** |

$^{a\text{-}d}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 10. Volatiles of 1-week-aged beef with different additives after 3 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ------------------------- (Total ion counts x $10^4$) ------------------------- | | | | | | |
| ***Hydrocarbons*** | ***7423*** | ***9028*** | ***5524*** | ***9680*** | ***8681*** | ***8653*** | ***1058*** |
| 2-Methyl-butane | 5483 | 5290 | 4387 | 8013 | 7857 | 7552 | 954 |
| Pentane | 1682$^{b}$ | 2889$^{a}$ | 832$^{b}$ | 1009$^{b}$ | 565$^{b}$ | 755$^{b}$ | 367 |
| Hexane | 0$^{c}$ | 203$^{b}$ | 305$^{ab}$ | 372$^{a}$ | 259$^{ab}$ | 345$^{a}$ | 29 |
| Heptane | 0$^{c}$ | 220$^{a}$ | 0$^{c}$ | 162$^{b}$ | 0$^{c}$ | 0$^{c}$ | 4 |
| Octane | 0$^{c}$ | 153$^{a}$ | 0$^{c}$ | 123$^{b}$ | 0$^{c}$ | 0$^{c}$ | 7 |
| 1-Penten | 256$^{a}$ | 270$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 15 |
| | | | | | | | |
| ***Ketones*** | ***3947*** | ***5795*** | ***4139*** | ***6036*** | ***3912*** | ***6964*** | ***1082*** |
| 2-Propanone | 3210 | 4725 | 3594 | 4588 | 3140 | 5484 | 872 |
| 2,3-Butanedione | 480 | 207 | 279 | 252 | 499 | 261 | 83 |
| 2-Butanone | 256 | 862 | 265 | 1194 | 271 | 1218 | 219 |
| | | | | | | | |
| ***Alcohols*** | ***3002***$^{bc}$ | ***4495***$^{a}$ | ***1916***$^{c}$ | ***3506***$^{ab}$ | ***2240***$^{bc}$ | ***3334***$^{ab}$ | ***353*** |
| Ethanol | 1317$^{b}$ | 2527$^{a}$ | 1204$^{b}$ | 2824$^{a}$ | 1548$^{b}$ | 2836$^{a}$ | 253 |
| 2-Pentanol | 512$^{a}$ | 311$^{b}$ | 584$^{a}$ | 340$^{b}$ | 548$^{a}$ | 370$^{b}$ | 42 |
| 1-Propanol | 153$^{a}$ | 107$^{b}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 7 |
| 2-Methyl-2-butanol | 0$^{b}$ | 273$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 13 |
| 1-Butanol | 180$^{a}$ | 197$^{a}$ | 127$^{b}$ | 144$^{b}$ | 144$^{b}$ | 127$^{b}$ | 8 |
| 1-Pentanol | 487$^{ab}$ | 858$^{a}$ | 0$^{b}$ | 196$^{b}$ | 0$^{b}$ | 0$^{b}$ | 130 |
| 1-Hexanol | 351$^{a}$ | 220$^{b}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 35 |
| | | | | | | | |
| ***Aldehydes*** | ***629***$^{b}$ | ***1365***$^{a}$ | ***326***$^{b}$ | ***0***$^{b}$ | ***58***$^{b}$ | ***0***$^{b}$ | ***245*** |
| Acetaldehyde | 443$^{a}$ | 369$^{b}$ | 326$^{b}$ | 0$^{c}$ | 58$^{c}$ | 0$^{c}$ | 22 |
| Hexanal | 186 | 995 | 0 | 0 | 0 | 0 | 249 |
| | | | | | | | |
| ***Cyclo compounds*** | ***579***$^{bc}$ | ***714***$^{ab}$ | ***405***$^{d}$ | ***759***$^{a}$ | ***516***$^{cd}$ | ***679***$^{ab}$ | ***41*** |
| Toluene | 0$^{b}$ | 121$^{a}$ | 0$^{b}$ | 109$^{a}$ | 0$^{b}$ | 115$^{a}$ | 7 |
| Benzene | 209 | 161 | 190 | 239 | 184 | 241 | 26 |
| Tetrahydro-furan | 369$^{a}$ | 432$^{a}$ | 215$^{b}$ | 410$^{a}$ | 332$^{ab}$ | 322$^{ab}$ | 35 |
| | | | | | | | |
| ***Total volatiles*** | ***15580***$^{ab}$ | ***21398***$^{a}$ | ***12311***$^{b}$ | ***19981***$^{ab}$ | ***15409***$^{ab}$ | ***19630***$^{ab}$ | ***1839*** |

$^{a-d}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 11. Volatiles of 2-week-aged beef with different additives after 3 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ------------------------- (Total ion counts x $10^4$) ------------------------- | | | | | | |
| ***Hydrocarbons*** | ***9510*** | ***8377*** | ***6739*** | ***6709*** | ***6380*** | ***4361*** | ***1176*** |
| 2-Methyl-butane | 7787 | 6651 | 6285 | 6036 | 5691 | 4067 | 1128 |
| Pentane | $1329^a$ | $1362^a$ | $86^b$ | $147^b$ | $196^b$ | $124^b$ | 117 |
| Hexane | $0^b$ | $0^b$ | $260^a$ | $247^a$ | $250^a$ | $169^a$ | 24 |
| 1-Penten | $270^a$ | $218^a$ | $0^c$ | $135^b$ | $0^c$ | $0^c$ | 20 |
| Octane | $123^b$ | $144^b$ | $106^b$ | $143^b$ | $241^a$ | $0^c$ | 17 |
| ***Ketones*** | ***3627*** | ***4241*** | ***3920*** | ***4752*** | ***3245*** | ***4574*** | ***945*** |
| 2-Propanone | 3237 | 3739 | 3595 | 3980 | 2905 | 3837 | 921 |
| 2,3-Butanedione | $138^a$ | $0^b$ | $167^a$ | $173^a$ | $186^a$ | $171^a$ | 12 |
| 2-Butanone | $251^b$ | $501^a$ | $157^b$ | $597^a$ | $153^b$ | $256^a$ | 61 |
| ***Alcohols*** | ***$3641^a$*** | ***$3871^a$*** | ***$2486^b$*** | ***$3955^a$*** | ***$1822^b$*** | ***$2101^b$*** | ***302*** |
| Ethanol | $1902^b$ | $2655^a$ | $1465^{bc}$ | $2624^a$ | $870^c$ | $1434^{bc}$ | 186 |
| 2-Propanol | 599 | 363 | 535 | 431 | 573 | 310 | 66 |
| 1-Propanol | $133^a$ | $0^b$ | $0^b$ | $0^b$ | $0^b$ | $0^b$ | 1 |
| 2-Methyl-2-butanol | $0^b$ | $0^b$ | $0^b$ | $258^a$ | $0^b$ | $0^b$ | 36 |
| 1-Butanol | 211 | 197 | 184 | 212 | 172 | 185 | 24 |
| 1-Pentanol | $594^{ab}$ | $655^a$ | $299^{bc}$ | $429^{abc}$ | $205^c$ | $170^c$ | 85 |
| 1-Hexanol | $200^a$ | $0^b$ | $0^b$ | $0^b$ | $0^b$ | $0^b$ | 20 |
| ***Aldehydes*** | ***$689^a$*** | ***$959^a$*** | ***$495^{ab}$*** | ***$379^{ab}$*** | ***$392^{ab}$*** | ***$0^b$*** | ***155*** |
| Acetaldehyde | 689 | 601 | 494 | 379 | 391 | 0 | 154 |
| Hexanal | $0^b$ | $357^a$ | $0^b$ | $0^b$ | $0^b$ | $0^b$ | 20 |
| ***Cyclo compounds*** | ***$551^{bc}$*** | ***$590^b$*** | ***$411^c$*** | ***$726^a$*** | ***$424^c$*** | ***$561^{bc}$*** | ***39*** |
| Toluene | $0^c$ | $112^b$ | $0^c$ | $134^a$ | $0^c$ | $111^b$ | 5 |
| Benzene | 224 | 204 | 178 | 172 | 182 | 192 | 29 |
| Tetrahydro-furan | $326^{ab}$ | $273^b$ | $232^b$ | $419^a$ | $241^b$ | $257^b$ | 37 |
| ***Total volatiles*** | ***18017*** | ***18038*** | ***14050*** | ***16521*** | ***12263*** | ***11597*** | ***1994*** |

[a-c] Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 12. Volatiles of 3-week-aged beef with different additives after 3 day storage at 4° C

| Compound | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ------------------------- (Total ion counts x $10^4$) ------------------------- | | | | | | |
| ***Hydrocarbons*** | ***$9455^{ab}$*** | ***$7242^{b}$*** | ***$12038^{a}$*** | ***$8089^{b}$*** | ***$1112^{c}$*** | ***$2261^{c}$*** | ***882*** |
| 2-Methyl-butane | $6898^{b}$ | $4139^{b}$ | $9639^{a}$ | $6154^{b}$ | $183^{c}$ | $411^{c}$ | 828 |
| 1-Pentene | $0^{b}$ | $0^{b}$ | $79^{a}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | 3 |
| Pentane | $1441^{ab}$ | $1815^{a}$ | $1409^{ab}$ | $1035^{bc}$ | $445^{c}$ | $886^{bc}$ | 176 |
| Hexane | $135^{b}$ | $213^{ab}$ | $335^{a}$ | $244^{ab}$ | $200^{ab}$ | $342^{a}$ | 35 |
| Heptane | $0^{b}$ | $262^{a}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | $210^{a}$ | 37 |
| 1-Penten | $644^{a}$ | $489^{a}$ | $281^{ab}$ | $345^{ab}$ | $0^{b}$ | $0^{b}$ | 93 |
| Octane | 336 | 322 | 293 | 308 | 282 | 411 | 67 |
| ***Ketones*** | ***4137*** | ***5588*** | ***4939*** | ***5838*** | ***5090*** | ***6278*** | ***986*** |
| 2-Propanone | 3403 | 4600 | 3917 | 4721 | 3832 | 4780 | 754 |
| 2,3-Butanedione | 549 | 262 | 750 | 462 | 1065 | 834 | 210 |
| 2-Butanone | 184 | 725 | 271 | 655 | 192 | 662 | 127 |
| ***Alcohols*** | ***3229*** | ***4199*** | ***5181*** | ***3537*** | ***2394*** | ***3078*** | ***642*** |
| Ethanol | 2050 | 2891 | 3997 | 2370 | 1386 | 1794 | 583 |
| 2-Propanol | 427 | 473 | 612 | 424 | 453 | 498 | 106 |
| 1-Butanol | 200 | 190 | 205 | 206 | 169 | 189 | 25 |
| 1-Pentanol | 551 | 643 | 366 | 537 | 385 | 596 | 168 |
| ***Aldehydes*** | ***$289^{bcd}$*** | ***$487^{abc}$*** | ***$71^{cd}$*** | ***$0^{d}$*** | ***$861^{a}$*** | ***$575^{ab}$*** | ***115*** |
| Acetaldehyde | $288^{abc}$ | $165^{bc}$ | $71^{bc}$ | $0^{c}$ | $644^{a}$ | $474^{ab}$ | 110 |
| Hexanal | $0^{c}$ | $321^{a}$ | $0^{c}$ | $0^{c}$ | $216^{b}$ | $100^{c}$ | 30 |
| ***Cyclo compounds*** | ***400*** | ***432*** | ***502*** | ***664*** | ***260*** | ***607*** | ***47*** |
| Toluene | $0^{c}$ | $107^{ab}$ | $0^{c}$ | $100^{b}$ | $0^{c}$ | $123^{a}$ | 5 |
| Benzene | $179^{a}$ | $126^{ab}$ | $205^{a}$ | $243^{a}$ | $0^{b}$ | $167^{a}$ | 43 |
| Tetrahydro-furan | $220^{ab}$ | $198^{b}$ | $296^{ab}$ | $320^{a}$ | $259^{ab}$ | $315^{a}$ | 25 |
| ***Total volatiles*** | ***$17509^{ab}$*** | ***$17947^{ab}$*** | ***$22731^{a}$*** | ***$18128^{ab}$*** | ***$9716^{c}$*** | ***$12798^{bc}$*** | ***1911*** |

$^{a-d}$ Values with different superscripts within a row are significantly different ($P$<0.05)
*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 13. Volatiles of 1-week-aged beef with different additives after 7 day storage at 4° C

| Compound | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | (Total ion counts x $10^4$) | | | | | | |
| ***Hydrocarbons*** | ***21425$^{ab}$*** | ***11575$^{b}$*** | ***29016$^{a}$*** | ***12989$^{b}$*** | ***12553$^{b}$*** | ***11011$^{b}$*** | ***3501*** |
| 2-Methyl-butane | 6646 | 8118 | 10858 | 12062 | 6890 | 10085 | 1965 |
| 1-Pentene | 3641$^{ab}$ | 0$^{b}$ | 5726$^{a}$ | 170$^{b}$ | 416$^{b}$ | 0$^{b}$ | 978 |
| Pentane | 328$^{b}$ | 2411$^{a}$ | 71$^{b}$ | 181$^{b}$ | 0$^{b}$ | 224$^{b}$ | 251 |
| 2-Pentene | 914$^{ab}$ | 0$^{b}$ | 1349$^{a}$ | 0$^{b}$ | 152$^{b}$ | 0$^{b}$ | 222 |
| 1,2-DCP* | 648$^{ab}$ | 353$^{bc}$ | 893$^{a}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 132 |
| 2-Methyl-2-butene | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 192$^{a}$ | 0$^{b}$ | 187$^{a}$ | 14 |
| 1,3-Pentadiene | 4938$^{a}$ | 379$^{b}$ | 4881$^{a}$ | 0$^{b}$ | 4153$^{a}$ | 300$^{b}$ | 383 |
| 1-Hexene | 416$^{a}$ | 0$^{b}$ | 281$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 63 |
| Hexane | 0$^{b}$ | 145$^{a}$ | 184$^{a}$ | 241$^{a}$ | 0$^{b}$ | 213$^{a}$ | 28 |
| 1-Heptene | 2525$^{a}$ | 0$^{b}$ | 3166$^{a}$ | 0$^{b}$ | 570$^{b}$ | 0$^{b}$ | 419 |
| 1, 4-Heptadiene | 679$^{ab}$ | 0$^{b}$ | 1002$^{a}$ | 0$^{b}$ | 258$^{ab}$ | 0$^{b}$ | 207 |
| Octane | 114$^{b}$ | 167$^{a}$ | 0$^{c}$ | 142$^{ab}$ | 0$^{c}$ | 0$^{c}$ | 10 |
| 1-Nonene | 574$^{a}$ | 0$^{b}$ | 599$^{a}$ | 0$^{b}$ | 111$^{b}$ | 0$^{b}$ | 106 |
| ***Ketones*** | ***1966*** | ***5499*** | ***3181*** | ***3529*** | ***2354*** | ***5254*** | ***1048*** |
| 2-Propanone | 1337 | 3805 | 2197 | 2767 | 1643 | 4339 | 898 |
| 2,3-Butanedione | 387$^{b}$ | 1410$^{a}$ | 519$^{b}$ | 392$^{b}$ | 431$^{b}$ | 551$^{b}$ | 191 |
| 2-Butanone | 0d | 284$^{ab}$ | 188$^{bc}$ | 369$^{a}$ | 129$^{c}$ | 363$^{a}$ | 33 |
| 2-Pentanone | 241$^{a}$ | 0$^{c}$ | 276$^{a}$ | 0$^{c}$ | 150$^{b}$ | 0$^{c}$ | 24 |
| ***Alcohols*** | ***25060$^{b}$*** | ***8095$^{c}$*** | ***39674$^{a}$*** | ***3119$^{c}$*** | ***31758$^{ab}$*** | ***2522$^{c}$*** | ***3147*** |
| Ethanol | 22753$^{b}$ | 3660$^{c}$ | 37677$^{a}$ | 2173$^{c}$ | 30007$^{ab}$ | 1721$^{c}$ | 2971 |
| 2-Pentanol | 408 | 584 | 631 | 498 | 674 | 547 | 90 |
| 2-Butanol | 208$^{a}$ | 0$^{c}$ | 185$^{b}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 6 |
| 1-Butanol | 179$^{b}$ | 500$^{a}$ | 169$^{b}$ | 267$^{b}$ | 146$^{b}$ | 253$^{b}$ | 28 |
| 3-Methyl-1-butanol | 769$^{a}$ | 0$^{b}$ | 1011$^{a}$ | 0$^{b}$ | 929$^{a}$ | 0$^{b}$ | 151 |
| 1-Pentanol | 397$^{b}$ | 1877$^{a}$ | 0$^{b}$ | 180$^{b}$ | 0$^{b}$ | 0$^{b}$ | 227 |
| 1-Hexanol | 344$^{b}$ | 1474$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 99 |
| ***Aldehydes*** | ***175$^{b}$*** | ***23317$^{a}$*** | ***140$^{b}$*** | ***0$^{b}$*** | ***0$^{b}$*** | ***0$^{b}$*** | ***310*** |
| Propanal | 0$^{a}$ | 1084$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 14 |
| 2-Methyl-propanal | 175$^{a}$ | 0$^{b}$ | 140$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 27 |
| Hexanal | 0$^{b}$ | 22233$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 323 |
| ***Cyclo compounds*** | ***1182$^{a}$*** | ***584$^{b}$*** | ***1162$^{a}$*** | ***656$^{b}$*** | ***802$^{ab}$*** | ***622$^{b}$*** | ***127*** |
| Benzene | 656$^{b}$ | 259$^{c}$ | 915$^{a}$ | 321$^{c}$ | 582$^{b}$ | 314$^{c}$ | 60 |
| Tetrahydro-furan | 525 | 324 | 247 | 334 | 219 | 307 | 126 |
| ***Others*** | ***46481$^{b}$*** | ***516$^{c}$*** | ***83867$^{a}$*** | ***224$^{c}$*** | ***47443$^{b}$*** | ***138$^{c}$*** | ***7141*** |
| Acetic acid | 1406$^{a}$ | 0$^{c}$ | 770$^{b}$ | 0$^{c}$ | 675$^{bc}$ | 0$^{c}$ | 177 |
| Acetic acid--ethyl ester | 44929b | 227$^{c}$ | 83096$^{a}$ | 0$^{c}$ | 46767$^{b}$ | 137$^{c}$ | 7022 |
| Butanoic acid-ethyl ester | 145$^{ab}$ | 289$^{a}$ | 0$^{b}$ | 223$^{a}$ | 0$^{b}$ | 0$^{b}$ | 44 |
| ***Total volatiles*** | ***96289$^{b}$*** | ***49586$^{c}$*** | ***157040$^{a}$*** | ***20517$^{c}$*** | ***94909$^{b}$*** | ***19548$^{c}$*** | ***9235*** |

$^{a\text{-}d}$ Values with different superscripts within a row are significantly different ($P$<0.05)

Abbreviation: Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, *1,2-dimethyl cyclopropane SEM; standard error of the means (n=4).

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Table 14. Volatiles of 2-week-aged beef with different additives after 7 day storage at 4° C

| | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| Compound | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | (Total ion counts x $10^4$) | | | | | | |
| ***Hydrocarbons*** | ***13788*** | ***18597*** | ***15647*** | ***12044*** | ***14682*** | ***23114*** | ***4969*** |
| 2-Methyl-butane | 6514 | 16602 | 10343 | 11120 | 11254 | 21544 | 3851 |
| 1-Pentene | 4349 | 0 | 3137 | 0 | 1243 | 0 | 1624 |
| Pentane | 302 | 1422 | 420 | 178 | 528 | 813 | 313 |
| Hexane | $0^{d}$ | $151^{c}$ | $269^{b}$ | $296^{b}$ | $263^{b}$ | $404^{a}$ | 31 |
| 1-Heptene | 1884 | 143 | 986 | 0 | 745 | 0 | 502 |
| Octane | $161^{c}$ | $278^{bc}$ | $167^{c}$ | $448^{a}$ | $412^{ab}$ | $352^{ab}$ | 41 |
| 1-Nonene | $575^{a}$ | $0^{b}$ | $323^{ab}$ | $0^{b}$ | $235^{ab}$ | $0^{b}$ | 121 |
| ***Ketones*** | ***3445*** | ***2559*** | ***3737*** | ***3735*** | ***3380*** | ***3362*** | ***514*** |
| 2-Propanone | 1959 | 2042 | 2736 | 2959 | 2282 | 2723 | 404 |
| 2,3-Butanedione | 791 | 362 | 583 | 395 | 607 | 269 | 161 |
| 2-Butanone | $158^{b}$ | $155^{b}$ | $168^{b}$ | $379^{a}$ | $262^{ab}$ | $369^{a}$ | 44 |
| 2-Pentanone | $345^{a}$ | $0^{b}$ | $250^{a}$ | $0^{b}$ | $227^{a}$ | $0^{b}$ | 33 |
| 3-Pentanone | $190^{a}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | $0^{b}$ | 14 |
| ***Alcohols*** | ***29475*** | ***4893*** | ***34632*** | ***4213*** | ***32140*** | ***1582*** | ***9847*** |
| Ethanol | 27119 | 2647 | 32333 | 2181 | 28854 | 1123 | 9666 |
| 2-Pentanol | $607^{b}$ | $1231^{a}$ | $791^{b}$ | $1087^{a}$ | $742^{b}$ | $0^{c}$ | 60 |
| 1-Propanol | $276^{a}$ | $0^{b}$ | $183^{a}$ | $0^{b}$ | $190^{a}$ | $0^{b}$ | 28 |
| 1-Butanol | $175^{b}$ | $375^{a}$ | $187^{b}$ | $365^{a}$ | $190^{b}$ | $309^{a}$ | 22 |
| 3-Methyl-1-butanol | $1000^{a}$ | $0^{b}$ | $976^{a}$ | $0^{b}$ | $1691^{a}$ | $0^{b}$ | 233 |
| 1-Pentanol | $0^{c}$ | $452^{ab}$ | $159^{bc}$ | 578a | $0^{c}$ | $149^{bc}$ | 90 |
| 1-Hexanol | $298^{b}$ | $185^{b}$ | $0^{c}$ | $0^{c}$ | $471^{a}$ | $0^{c}$ | 43 |
| ***Aldehydes*** | ***$0^{b}$*** | ***$6608^{a}$*** | ***$695^{b}$*** | ***$0^{b}$*** | ***$301^{b}$*** | ***$0^{b}$*** | ***700*** |
| 2-Methyl propanal | $0^{c}$ | $0^{c}$ | $695^{a}$ | $0^{c}$ | $300^{b}$ | $0^{c}$ | 59 |
| Hexanal | $0^{b}$ | $3559^{a}$ | $0^{b}$ | $0^{b}$ | 0b | $0^{b}$ | 871 |
| ***Cyclo compounds*** | ***$745^{ab}$*** | ***$582^{bc}$*** | ***$920^{a}$*** | ***$436^{c}$*** | ***$772^{ab}$*** | ***$594^{bc}$*** | ***68*** |
| Benzene | $533^{ab}$ | $279^{b}$ | $692^{a}$ | $435^{ab}$ | $561^{ab}$ | $311^{b}$ | 72 |
| Tetrahydro-furan | $212^{b}$ | $303^{a}$ | $227^{b}$ | $0^{c}$ | $211^{b}$ | $283^{a}$ | 16 |
| ***Others*** | ***$43501^{a}$*** | ***$0^{b}$*** | ***$40104^{a}$*** | ***$230^{b}$*** | ***$38001^{a}$*** | ***$734^{b}$*** | ***8968*** |
| Acetic acid | 9280 | 0 | 1153 | 0 | 756 | 455 | 3200 |
| Acetic acid,ethyl ester | $80998^{a}$ | $0^{b}$ | $38950^{b}$ | $229^{b}$ | $37245^{b}$ | $279^{b}$ | 11348 |
| ***Total volatiles*** | ***$90954^{a}$*** | ***$33241^{ab}$*** | ***$95735^{a}$*** | ***$20657^{b}$*** | ***$89276^{a}$*** | ***$29387^{ab}$*** | ***16074*** |

[a-d] Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

Table 15. Volatiles of 3-week-aged beef with different additives after 7 day storage at 4° C

| Compound | Cont | | A+E | | A+E+S | | |
|---|---|---|---|---|---|---|---|
| | Non-IR | IR | Non-IR | IR | Non-IR | IR | SEM |
| | ------------------------- (Total ion counts x $10^4$) ------------------------- | | | | | | |
| ***Hydrocarbons*** | ***29782$^{a}$*** | ***34241$^{a}$*** | ***33426$^{a}$*** | ***13372$^{b}$*** | ***5648$^{b}$*** | ***4062$^{b}$*** | ***4761*** |
| 2-Methyl-butane | 19251$^{b}$ | 31663$^{a}$ | 16836$^{bc}$ | 12549$^{bc}$ | 4523$^{c}$ | 3049$^{c}$ | 3537 |
| 1-Pentene | 5971$^{b}$ | 192$^{b}$ | 10875$^{a}$ | 204$^{b}$ | 305$^{b}$ | 0$^{b}$ | 1518 |
| Pentane | 507$^{b}$ | 2026$^{a}$ | 421$^{b}$ | 307$^{b}$ | 211$^{b}$ | 592$^{b}$ | 306 |
| 2-Pentene | 991$^{b}$ | 0$^{c}$ | 1425$^{a}$ | 0$^{c}$ | 114$^{c}$ | 0$^{c}$ | 109 |
| 1-Hexene | 433$^{a}$ | 0$^{b}$ | 577$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 81 |
| Hexane | 199 | 359 | 314 | 310 | 230 | 420 | 56 |
| 1-Heptene | 2427$^{a}$ | 0$^{b}$ | 2976$^{a}$ | 0$^{b}$ | 264$^{b}$ | 0$^{b}$ | 191 |
| Heptane | 0$^{b}$ | 261$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 303$^{a}$ | 46 |
| 1, 4-Heptadiene | 809 | 0 | 1458 | 0 | 0 | 0 | 385 |
| Octane | 430 | 574 | 494 | 312 | 421 | 510 | 111 |
| | | | | | | | |
| ***Ketones*** | ***5091*** | ***4327*** | ***5119*** | ***5421*** | ***4349*** | ***5798*** | ***644*** |
| 2-Propanone | 3174 | 3444 | 3940 | 4326 | 3062 | 4088 | 455 |
| 2,3-Butanedione | 1049 | 502 | 235 | 635 | 925 | 1375 | 343 |
| 2-Butanone | 332$^{ab}$ | 379$^{ab}$ | 238$^{ab}$ | 459$^{a}$ | 152$^{b}$ | 334$^{ab}$ | 64 |
| 2-Pentanone | 534$^{b}$ | 0$^{c}$ | 703$^{a}$ | 0$^{c}$ | 210$^{c}$ | 0$^{c}$ | 56 |
| | | | | | | | |
| ***Alcohols*** | ***47362$^{a}$*** | ***5252$^{b}$*** | ***40209$^{a}$*** | ***3510$^{b}$*** | ***33828$^{a}$*** | ***2771$^{b}$*** | ***6125*** |
| Ethanol | 42623$^{a}$ | 3265$^{b}$ | 34774$^{a}$ | 2090$^{b}$ | 31466$^{a}$ | 1582$^{b}$ | 6009 |
| 2-Propanol | 803$^{ab}$ | 556$^{ab}$ | 1071$^{a}$ | 414$^{b}$ | 864$^{ab}$ | 521$^{ab}$ | 136 |
| 1-Propanol | 1735 | 329 | 2979 | 0 | 0 | 0 | 840 |
| 2-methyl-1-propanol | 314$^{a}$ | 0$^{c}$ | 211$^{b}$ | 336$^{a}$ | 182$^{b}$ | 0$^{c}$ | 24 |
| 1-Butanol | 241$^{c}$ | 467$^{a}$ | 277$^{bc}$ | 401$^{ab}$ | 300$^{bc}$ | 402$^{ab}$ | 33 |
| 3-Methyl-1-butanol | 1346 | 0 | 598 | 0 | 835 | 0 | 414 |
| 1-Pentanol | 297$^{b}$ | 632$^{a}$ | 296$^{b}$ | 268$^{b}$ | 179$^{b}$ | 264$^{b}$ | 64 |
| 1-Hexanol | 332$^{a}$ | 461$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 71 |
| | | | | | | | |
| ***Aldehydes*** | ***216$^{b}$*** | ***1226$^{a}$*** | ***137$^{b}$*** | ***0$^{b}$*** | ***0$^{b}$*** | ***0$^{b}$*** | ***152*** |
| 2-methyl-Propanal | 216$^{a}$ | 0$^{c}$ | 136$^{b}$ | 0$^{c}$ | 0$^{c}$ | 0$^{c}$ | 21 |
| Hexanal | 0b | 1226$^{a}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 0$^{b}$ | 150 |
| | | | | | | | |
| ***Cyclo compounds*** | ***672$^{ab}$*** | ***456$^{c}$*** | ***792$^{a}$*** | ***557$^{bc}$*** | ***394$^{c}$*** | ***470$^{c}$*** | ***42*** |
| Benzene | 476$^{a}$ | 188$^{b}$ | 529$^{a}$ | 333$^{b}$ | 197$^{b}$ | 235$^{b}$ | 37 |
| Tetrahydro-furan | 195 | 268 | 262 | 224 | 196 | 234 | 18 |
| | | | | | | | |
| ***Others*** | ***58539$^{a}$*** | ***1427$^{b}$*** | ***32934b*** | ***2900$^{b}$*** | ***9079$^{b}$*** | ***371$^{b}$*** | ***7726*** |
| Acetic acid | 4029 | 133 | 231 | 178 | 0 | 0 | 982 |
| Acetic acid,ethyl ester | 54509$^{a}$ | 1294$^{b}$ | 32702$^{ab}$ | 2722$^{b}$ | 9079$^{b}$ | 371$^{b}$ | 8328 |
| | | | | | | | |
| ***Total volatiles*** | ***143234$^{a}$*** | ***48228$^{b}$*** | ***114572$^{a}$*** | ***26073$^{b}$*** | ***53720$^{b}$*** | ***14286$^{b}$*** | ***13854*** |

$^{a\text{-}d}$ Values with different superscripts within a row are significantly different ($P$<0.05)

*Abbreviation:* Non-IR; non-irradiated samples, IR; irradiated samples, Cont; control, A; ascorbic acid, E; vitamin E, and S; sesamol, SEM; standard error of the means (n=4).

# CHAPTER 6. GENERAL CONCLUSION

Food irradiation is being recognized as one of the most effective method to control pathogenic microorganisms. Ground beef, because of its way of preparation, is more susceptible to contamination than other meat products. Therefore, applying irradiation to ground beef, in order to eliminate pathogens, will be an effective solution. However, irradiation affects quality change in a way that will limit its usage. The most noticeable and important quality changes in ground beef because of irradiation include color changes, off-odor production and accelerated lipid oxidation. Color of irradiated ground beef will change to unattractive brown or green color, which will definitely affect consumer acceptance of irradiated meat. Irradiation off-odor and lipid oxidation are also very important quality parameters that impact consumers' decision to buy ground beef. Reducing agents and antioxidant are being used in order to control those changes.

Irradiating ground beef with different fat contents, up to 20%, did not influence the effect of irradiation on lipid oxidation and the volatiles production. Using ascorbic acid in combination with α-tocopherol and sesamol was effective in slowing down lipid oxidation caused by irradiation. Redness of irradiated beef was not affected by fat contents. Irradiation lowered ORP and increased the production of CO in ground beef without any influence from fat contents or meat aging. Beef aging affected lipid oxidation caused by irradiation. Lipid oxidation was accelerated by aging. Aging did not influence the decreasing of beef redness caused by irradiation. The amounts of volatiles aldehydes produced by irradiation were tripled as beef age increased. However, ascorbic acid and α-tocopherol were effective in reducing these volatiles. Applying ascorbic acid and antioxidants by either mixing or spraying, did not affect any quality of irradiated ground beef except for the spraying application where it lead to more production of aldehydes, hydrocarbons and total volatiles compared with mixing. Also, the ORP of ground beef sprayed with antioxidants was not as low as that with mixing. Therefore, using beef with up to 20% fat would not change any irradiated beef quality, while using aged beef will accelerate lipid oxidation. Adding antioxidants by mixing instead of spraying would be better for ground beef to improve quality of irradiated ground beef during storage.

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