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The synergistic effect of non-thermal techniques and modified atmosphere packaging in food preservation

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Abstract**—** *Consumer's demand for food products that retain the natural properties and microbiologically safer food has promoted the use of non-thermal techniques for the reduction of microbial load and inactivation of enzymatic activity. However, the bacterial spores and some enzymes show high resistance against non-thermal techniques. Therefore, the application of non-thermal techniques with modified atmosphere packaging (MAP) represents an emerging method to increase the shelf life of food products. These combined preservation techniques reduced the microbial load, increase the shelf life without effecting the sensory attributes of food products. The surface of food products would benefit from the preservative effect of both non-thermal techniques and MAP. These integrated techniques are more energy efficient and better preservative effect than the single preservation technique. The use of MAP with non-thermal techniques reduces the intensity of nonthermal treatments required to achieve the desirable results. This review discusses the advantages that may be derived from the combined use of non-thermal techniques and MAP in the preservation of food.*

Keywords**—** ***Food Safety, Innovative Technology, Modified Atmosphere packaging, non-thermal processing, Quality Control.***

I. INTRODUCTION

The fresh fruits and vegetables should consume within 7 to 8 days after harvesting because they have a limited shelf life up to 5 days [1]. After harvesting of food products different physical, chemical, enzymatic, and microbiological changes get started at a higher rate that reduced the quality attributes of fresh products. The washing of fruits or vegetables after harvesting removes the soil residues and plant debris but it has less effectiveness for microbial decontamination. The use of preservation techniques improves the quality deterioration and extending the shelf life of food products by inactivating the microorganisms and enzymes that are responsible for the spoilage [2]. The best preservation technique is one which improves the quality of food products without changing the nutrient contents and sensory attributes. Non-thermal preservation techniques improve the shelf life and microbiological safety of food without affecting the freshness of fruit juice, while thermal techniques negatively affect the freshness, nutrient contents and sensory attributes of food products. Food industries prefer those preservation techniques that retain the freshness of food products because consumer likes natural and fresh food products [3].

Thermal techniques are mostly use in the preservation of food products. Although they increase the shelf life of food products, the use of high-temperature negatively affects the quality attributes like reduction in the nutrient contents, sensory attributes, inactivation of enzymes and coagulation of proteins [4]. It's the need of the hour to find a technique that fulfills the requirements of consumers in terms of better sensory attributes, food safety and less harmful effect on the health of consumer [5]. Therefore, the application of non-thermal techniques in the processing and preservation of food products gaining popularity. Nonthermal techniques are the best alternative for the processing and preservation of food products, but they have a certain limit due to the resistance of some bacterial spores and certain enzymes. Sometimes, the use of single preservation does not inactivate all the spoilage causing agents. To get a better result for food preservation, application of non-thermal techniques is applied in combination with other food preservation techniques. A combination of different preservation techniques is preferred because the synergic effect of combined preservation techniques inactive all the microorganisms and reduced the time of processing. The integration of non-thermal techniques with other preservation techniques give better results in terms of the inactivation of enzymes and the destruction of bacterial spores [2]. Application of non-thermal techniques together with modified atmosphere packaging (MAP) in the preservation of food reduced the loss of nutrient contents retains better sensory attributes and extends the shelf life as compared to the use of a single non-thermal preservation technique. The integration of preservation method has been used successfully in different countries for centuries without the proper scientifically understanding like a combination of heat, water activity and storage conditions [6, 7].

The use of non-thermal techniques with other preservation techniques is not always beneficial. Sometimes treatments of food with a combination of processing techniques increase the harmful effects. Reduction in the intensity of nonthermal techniques is needed when they are applied together with MAP [2].

Table:1 Summary of deteriorative changes in food products responsible for spoilage of food

Deteriorative changes	**Reason behind deteriorative changes**	**Consequences**	**Citation**
Enzymatic changes	Phenolase, Amylase, pectin methyl esterase Phenylalanine ammonia lyase Polyphenol Oxidase Peroxide	Oxidation of phenolic compounds, Conversion of sugar to starch, post-harvest demethylation of pectin is responsible for the softening and ripening of tissue.	[8]
Sensory changes	Lipid oxidation enzymatic browning.	Essential fatty acid loss, production of toxic substance.	[9]
Change in color	Loss of Chlorophyll due to phenophytinisation or photo-oxidation. Loss of Anthocyanin at high pH. Loss of Carotenoids due to oxidation.	Green color lost, loss of reddish color	[9]
Flavor change	Hydrolysis, lipolysis, and proteolysis	Off-flavor mainly due to aldehydes and ketones (rancid taste).	[9]
Nutritional changes	Light, temperature, water activity and temperature are responsible for the degradation of nutrients such as ascorbic acid.	Loss of ascorbic acid,	[9]
Physical changes	Bruising, absorption of moisture, dehydration, moisture migration, starch gelatinization, chill injury, crystal growth and emulsion breakdown are different physical factors affect the shelf life of food products.	Economic losses, loss in weight, increase in senescence, sugar bloom, fat bloom, phase separation	[9]

Microbial changes	Bacteria yeast, mold and fungus are responsible for the microbial spoilage of food.	They reduced the shelf life by accelerating the decay process and its results in loss of nutritional quality and sensory attributes	[9]
Microbiological changes	Insects and rodents	They cause considerable off flavor, acceleration of decay process and nutitional quality.	[10]

II. MODIFIED ATMOSPHERE PACKAGING (MAP)

Modified atmosphere is helpful in the preservation of food while at the same time retain the fresh attributes of food products [11]. In a modified atmosphere packag (MAP), the atmosphere of gases around the foods in packaging material is altered to extend the shelf life and maintain the quality of foods. MAP is not a new concept in the food industry [12]. The use of MAP for the preservation of food is started in the 1930s when research was done on the modification of atmosphere gases for the preservation of food. Active modified atmosphere and passive modified atmosphere are two different types. In active MAP, the desired atmosphere in the package is produced by displacing the air with a mixture of desired gases (inert gas and active gas) [13]. In passive MAP, the desired atmosphere is produced by the respiration of food in the package and the diffusion of gases produced by respiration from the packaging barrier [14]. A high concentration of carbon dioxide in the MAP a preservative effect by inhibiting the growth of spoilage microorganism. The shelf life of food products is limited in the presence of air because a high concentration of oxygen in the air increases the growth of aerobic microorganisms and oxidation of fat [13].

The normal level of nitrogen in the atmosphere is 78% while the oxygen percentage is 21% and the carbon dioxide percentage in the atmosphere is 0.03%. Food products kept in the air have limited shelf life due to a reduction in the quality attributes caused by microorganisms and oxygen reactions. MAP is used to protect the food products from quality reduction by altering the gas composition within the packaging. Modification of atmosphere within the packaging is done by decreasing the level of oxygen and increasing the content of carbon oxide or nitrogen. The level of oxygen is kept low because it is responsible for the rapid growth of aerobic microbes and some enzymatic reactions like oxygenation of myoglobin and oxidation of unsaturated fats. In some exceptional cases, a high level of oxygen within the packaging is needed for the respiration of fruits, vegetables and red color retention in meats [15]. The level of carbon dioxide is kept high within MAP because it inhibits the growth of aerophilic bacteria that cause spoilage of food. The level of carbon dioxide applied in atmosphere packaging varied from 25% to 100% depending upon the type of food. Preservation of fats or hard cheeses requires a high level of carbon oxide within the MAP [16]. Nitrogen is inert gases used in the MAP in place of oxygen to control the rancidity and oxidation in fat-rich food products. It is also used as filler in packaging to control the collapse in the packaging of food products that absorbed carbon dioxide. Carbon monoxide is also used in MAP for the preservation of food, but it is a highly toxic gas and its use within modified packaging is not proved by authorities owing to its health hazards. Mostly a mixture of three gases is used in MAP to obtain the desire preservation effect [17].

MAP prevents the spoilage caused by bacteria in many food products, especially minimally processed fruits, or vegetables. Alteration in the gaseous components in the packaging atmosphere may increase the shelf life of food products by decreasing the rate of respiration [18]. The combination of MAP with non-thermal treatments increases the sensitivity of bacteria for non-thermal techniques [1].

III. TYPES OF NON-THERMAL TECHNIQUES

There are many types of non-thermal processing methods are available that enhance the quality of food without the application of heat. These methods are sonication, radiation, ultra-high pressure, magnetic field. Pulsed electric field, pulsed light field and ozone [19].

3.1. Synergistic effect of ultrasonication in food preservation

3.1.1. Inactivation of microbes

Microorganisms directly or indirectly enter the food and decrease the quality and safety of food products. The presence of a low level of microbial load on the minimally processed food product is an indicator of the long shelf life and high safety of food products. the ultrasound is used as an alternative to thermal techniques for the inactivation of microorganisms. The antimicrobial effect of ultrasound is due the cavitation phenomenon. The change in pressure and temperature during cavitation produce free radicals that case disruption of microbial cell wall, DNA and cell membrane damage. The different types of bacteria due to their different membrane structure show different response against ultrasound [20, 21]. The behavior of gram positive and gram negative is different against ultrasonication waves. The certain microorganisms specially spores show resistance again ultrasound treatment [22]. Therefore, ultrasonication is used with MAP to inactivate the resistant microorganisms.

Storage of minimally processed food products under MAP reduces the risk of molds, yeast and aerobic bacterial counts. Treatment of food products with ultrasound before storage in MAP reduces the proliferation of food spoilage microbes. The level of decay of the untreated food product kept under air conditions was higher than the food treated with ultrasound and packaged in modified atmosphere [23].

Application of ultrasonication treatment to the beef samples kept under vacuum packaging and MAP reduced the load of lactic acid bacteria. The minimum increase in the LAB counts was seen on the beef sample treated with US-MAP than the control sample of beef after 8 weeks of storage [24].

Treatment of fresh-cut cucumber samples with ultrasound and kept under MAP reduce the total number of bacterial counts, yeast and mold after 15 days of storage. The total no of bacterial counts, mold and yeast of untreated fresh-cut cucumber was 6.72 CFU/g, 4.17, 3.85 and 3.69 log CFU/g respectively. The total number of colonies of fresh-cut cucumber samples treated with ultrasound for 5 min, 10 min and 15 min was 6.72, 5.98, 5.28 and 5.14 log CFU/g, respectively whereas mold and yeast of these treatments of fresh-cut cucumber were 4.17, 3.85 and 3.69 log CFU/g, respectively. Fresh-cut cucumber treated with ultrasonication treatment for 10 min with MAP was highly effective to inhibit the growth of bacteria, yeast and molds [25]. However, the application of combined treatment ultrasound and MAP to the Pakchoi did not show any reduction of microbial load during the storage [26].

3.1.2. Effect on enzymes

The changes induced by endogenous enzymes in plant tissue during storage may be desirable or undesirable. PAL, PPO and POD involved in the oxidation of phenolics compounds which result in browning of fruits or vegetables [27]. The Pectin methyl esterase involved in the autolysis of cell which result in increased the biosynthesis of ethylene. The Pectin methyl esterase also involves in demethylation of pectin result in softening of fruits and vegetables tissue. α-amylase, β-amylase and starch phosphorylase degrade the starch into simple sugar which result in high concentration of reducing sugar, and low concentration of total sugar. The different factor that affect the activity of enzymes are temperature, moisture and storage time [28, 29]. The Pakchoi sample treated with UT-10min + MAP showed reduced activity of POD and PPO enzymes throughout the storage than the control sample. The pakchoi sample treated with US-10 min and kept under MAP showed the lowest activity of POD and PPO throughout the storage period [26]. [30] reported that the application of ultrasound to the Psidium guajava kept under MAP inactive the POD during storage.

3.1.3. Synergistic effect on the quality attributes of food

Total soluble solid is an important parameter for the measurement of the quality of fruits and vegetables. Total soluble contents in fruits were increased during the early period of storage due to the after-ripening of fruits and loss of water by evaporation. With the increase in the storage of fruits or vegetables total soluble solid decreased due to the consumption of nutrients for the maintenance of normal physiology, respiration and metabolic activities of fruits and vegetables [31]. The total soluble solid of fresh cut cucumber was decreased during storage due to senescence The treatment of fresh cut cucumber with ultrasonication reduce the degradation of total soluble solid during storage. The fresh-cut cucumber treated with ultrasound for 10 mint and kept under MAP was lower than untreated fresh-cut cucumber sample [25]. Application of ultrasound together with MAP to the Pakchoi delays the degradation of TSS than the control sample of Pakchoi. [32].

The ascorbic acid of fruits and vegetables were decreased during storage. When fruits and vegetables were treated with ultrasound for 10 minutes and packed in MAP, a high level of ascorbic acid was found at the end of storage. The decrease in the ascorbic acid contents of the control sample of fresh-cut cucumber was 49.55% whereas in cucumber treated with UT-5 min + MAP, UT-10 min + MAP and UT-15 min + MAP was 41.14%, 32.83% and 44.24% respectively at the end of storage. The reduction in ascorbic acid of fresh-cut cucumber treated with UT-10 min + MAP was lower than all other treatments during storage [25]. The application of ultrasound together with MAP reduce the decrease in content during storage. Different samples of Pakchoi were subjected to UT-5 min + MAP, UT-10min + MAP, UT-15 min + MAP and it was found that Pakchoi treated with UT-10min + MAP showed a higher level of ascorbic acid than all other treatment of Pakchoi at the end of storage [26]. [30] reported that ultrasound treatment with MAP reduced the loss of ascorbic acid of Psidium guajava during the 30 days of storage. The reduction in degradation of ascorbic acid in fruits and vegetables during storage is due to is due cavitation effect produced by ultrasound treatment and low level of dissolved oxygen in MAP [33].

Antioxidant activity of untreated fruit juices decreased due to the degradation of phenolics during storage. The fruit juices subjected to ultrasonication showed better antioxidant activity than untreated juice. The fruit juices treated with ultrasonication and packed in MAP showed high antioxidant activity. The combined application of Ultrasonication, anti-browning treatments to the fresh-cut apple Packed in MAP showed high antioxidant activity due to the low degradation of phenolics during storage. [34].

The formation of malondialdehyde compound is an indication of lipid peroxidation. The increase in the MDA content was observed during storage. The combined application of ultrasonication with modified atmosphere packaging reduced the formation MDA compound in fresh-cut cucumber. After 15 days of storage, production of MDA in the control sample of fresh-cut cucumber was 3.42 nmol/g whereas, in fresh-cut cucumber samples treated with US5min+MAP, US10min+MAP and US15min+MAP were 2.53 nmol/g, 2.15 nmol/g and 2.78 nmol/g respectively. The lowest MDA was produced in fresh-cut cucumber treated with US10+MAP. This is because US treatment of fresh-cut cucumber for 10 min and packaging under MAP maintain the integrity of the cell membrane and slowdown the senescence of fresh-cut cucumber [25] [26]. A similar type of effect of US treatment was seen in mushrooms where US treatment for 10 minutes decrease the MDA production in mushrooms kept under a relative humidity of 95% [35].

The high rate of respiration and loss of water increase the weight loss of fruits and vegetables during storage. The application of ultrasonication with modified atmosphere packaging reduced the weight loss of fresh-cut cucumber during storage. It was observed that application of ultrasonication for 10 minutes with MAP reduces the weight loss of fresh-cut cucumber by 8.63%. This is due to the protection of hydrogen bonds between molecules of water and macromolecules of fresh-cut cucumber [25]. Application of ultrasonication together with Modified atmosphere Packaing also reduce the weight loss of Pakchoi during storage. [26]. [24] reported that beef samples treated with ultrasonication and kept under modified atmosphere packaging also show less weight loss as compared to untreated sample. The *Psidium guajava* treated with US-10 min and kept under MAP showed a lower reduction in weight than the control sample during storage [30].

The water holding capacity of untreated beef decreased during storage. During the 3 to 6 days of storage, the water holding capacity of beef treated with US-MAP or US-VP was higher than the control sample [24].

Storage of fruits or vegetables without any treatment results in a change in the volatile compounds and deterioration of the flavor quality. Fruits or vegetables treated with ultrasound combined with MAP have a better quality of the flavor at the end of storage. Fresh-cut cucumber treated with ultrasound for 10 minutes and kept under MAP maintain a high quality of flavor because ultrasound treatment with a modified atmosphere prevents the change in the aromatic compound responsible for the flavor. The changes in color and decrease in firmness of fresh-cut cucumber samples treated with ultrasound (10 min) and packed under MAP were less than untreated samples after 15 days of storage [25].

The application of ultrasonication with MAP reduces the increase in yellowness of leaves during storage. Pakchoi samples treated with ultrasonication for 10 min and kept under MAP showed the lowest yellowness of leaves than the control sample during the storage [26]. Ultrasonication treatment with MAP preserves the original flavor of Psidium guajava during the storage. [30] reported that The Psidium guajava treated with US-10 min and kept under MAP showed retain better flavor than the control sample during storage.

The integration of the ultrasound technique with MAP or vacuum packaging also retained the texture, color, and flavor of beef fresh as compared to beef sample without any treatment. The beef sample maintains its texture better in vacuum packaging as compared to MAP because bacteria yeast and mold are unable to grow in it the absence of oxygen [24].

3.2. Irradiation

3.2.1. Synergistic effect of irradiation and MAP in food preservation

A combination of irradiation and MAP was proved effective to control all the aerobic bacteria and coliforms of Chinese cabbage than single preservation method. Gamma irradiation dose up to 0.5 kGy is applied to Chinese cabbage, reduced the initial load of aerobic bacteria up to 2–3 log CFU/g. Irradiation of Chinese cabbage packaged under MAP reduced the coliform counts to undetectable limits after 3 weeks of storage. Lactic acid bacteria continue to grow in the presence of a high level of carbon dioxide during storage, but irradiation of Chinese cabbage inhibits the growth of lactic acid bacteria in the presence of a high level of carbon dioxide. A dose of 1 kGy of irradiation with MAP reduced all the spoilage causing microbes and increasing the shelf life of Chinese cabbage [36]. Carrots treated with irradiation (2 kGy) improved the quality and shelf life by destroying the microbes that cause spoilage [37].

A combination of gamma irradiation (1.0, 1.5, and 2.0 kGy) with MAP was proved effective to reduce the microbial load of shiitake mushrooms. Small brown spots were developed on the shiitake mushrooms after 4 days when alone modified atmosphere package was used for the preservation. After 8 days, small brown spots on the shiitake mushroom were changed into black spots due to the high microbial activity of pseudomonas. Black spots on the shiitake mushroom is an indication of decay of the mushroom and end of shelf life. The shelf life of shiitake mushrooms was increased by treating with gamma irradiation (1.0, 1.5, and 2.0 kGy) + MAP that prevents the development of black spots by inactivating the activity of pseudomonas [38].

The combined effect of gamma irradiation and MAP on the strawberry increase the shelf life from 5 days to 7 days without any evidence of fungal decay and any change in the sensory attributes. The spoilage agent of strawberry is *B. cinerea* that causes grey mold disease and decreases the shelf life of strawberry by changing the texture and appearance. After 7 days, mold decay of the non-irradiated strawberry stored under aerobic packaging was started. While strawberry sample irradiated by a dose of 1.0 kGy and stored under MAP showed not any sigh of mold growth after 14 days of storage [39].

Irradiation of grated carrots stored under MAP reduced the *E. coli* from log 6 to log 2 while the reduction of *E. coli* of irradiated grated carrots stored under air was from 6 to 3 log. A difference of one log exists between the grated carrots stored under MAP and air conditions during 20 days of storage. There was not any *E. coli* colony detected on the grated carrots treated with irradiation at a dose greater than 0.3 kGy and stored under MAP. A 1–2 log CFU/g bacteria were seen on irradiated grated carrot samples stored under air between 5 days and 15 days. Complete elimination of bacteria in grated carrots require treatment with irradiation by dose 0.6 kGy under air and a dose of 0.3 kGy stored under MAP [40]. Irradiated cut romaine lettuce (0.15 and 0.35 KGy) kept under MAP reduced aerobic counts, yeasts and molds by 1 log during storage for 22 days [41].

Saffron treated with gamma irradiation decrease the microbial load while reduction of the microbial load was higher in irradiated saffron kept under MAP. The untreated saffron sample showed limited shelf life due to the high load of *E. coli*, mold, and yeast [39].

Irradiation of spices by doses of 12 kGy and 7 kGy reduced the microbial load (bacteria, mold and yeast) to an undetectable level. Although irradiation itself is effective to improve the shelf life of spices by destroying spoilage microorganisms but is a combination with a modified atmosphere that gives an extra benefit [42].

Figs treated with irradiation by dose 1 kGy packed under MAP exhibit the lowest microbial load then followed by fig samples treated with irradiation by dose 0.5 kGy packed under MAP, irradiation alone by dose 1 kGy, 0.5 kGy and modified atmosphere package alone. The microbial load of figs samples treated with the irradiation (1 kGy) + MAP, (0.5 kGy) + MAP, only irradiation by dose 1 kGy, 0.5 kGy and non-irradiated figs sample packed under MAP was 2.56, 3.17, 3.42, 3.86, 4.17 CFU/g respectively. Figs sample without any treatment showed the highest microbial load of 4.71 CFU/g [43].

Microorganisms responsible for the quality deterioration of the chicken meat are LAB, *B. thermosphacta*, Enterobacteriaceae, *Pseudomonas* spp. and yeast. Irradiated chicken meat at dose 4 kGy and kept under MAP1 (30% CO_2/70% N_2) and MAP2 (70% CO_2/30% N_2,) had low microbial load than all meat samples treated with irradiation or MAP1 only [44].

3.2.2. Synergistic effect on the quality attributes of food product

The Application of gamma irradiation(1.0, 1.5, and 2.0 kGy) and modified atmosphere packaging to Shiitake mushrooms lower the degradation of phenolic contents and MDA production during Storage [38].

. The increase in MDA level of Shiitake mushroom treated with irradiation (1, 1.5 and 2 KGy) and kept under MAP were increased upto 31.7%, 70.1 and 59.2 % respectively while MDA level of non-irradiated shiitake mushroom kept under MAP only was increased approximately 100% [45].

[46] reported that the Level of sweetness in the fruit or vegetables is indicated by TSS and it increases over time as the fruit mature to produce sweeter fruits. The concentration of total soluble sugar is considered the predominant indicator of postharvest losses in harvested fruits and vegetables. The concentration of total soluble sugar increase in shiitake mushroom samples treated with irradiation + MAP at the same rate as in the MAP during the first 12th day. However higher increase in the sugar level was observed in the shiitake mushrooms treated with irradiation (1.0 kGy) and MAP during whole storage while a small increase in sugar was observed in the shiitake mushrooms sample kept under MAP only [45].

After harvesting, TSS values of fruits and vegetables increase over time due to the respiration. The increase in TSS was slow in the fig samples treated with combined preservation methods irradiated (0.5, 1KGy) + MAP and alone MAP. Intergradation of Irradiation with MAP or alone MAP reduced the rate of respiration and metabolic changes in harvested figs result in less increase of TSS during storage. Irradiation of figs by dose 0.5 kGy and MAP was found effective to reduce the increase in TSS of fruits or vegetables during storage [43].

The high value of titratable acidity of fruits or vegetables means the presence of a high concentration of total acid within fruits or vegetables [47]. TA of all fruits or vegetables was decreased over time due to the consumption of organic acid for the production of new compounds and as a substrate for respiration during ripening [48]. Treatment of fresh fruits or vegetables with irradiation decreases the TA due to the irradiation injury [49]. Irradiated figs by dose 1 kGy had a low value of TA while irradiated figs by dose 0.5 kGy. Small changes in TA of figs sample treated with irradiation and kept under MAP were observed than fig samples treated with irradiation or MAP only [43]. Titratable acidity of salted Chinese cabbage was increased during storage due to the growth of lactic acid bacteria. Irradiation of Chinese cabbage packaged under MAP delay the change of titratable acidity for 3 weeks by reducing the growth of lactic acid bacteria. MAP did not have any effect on the TA of Chinese cabbage [36].

The weight loss of shiitake mushroom depends on the water loss by transpiration and the rate of respiration. The weight losses were increased over time during the storage. Fruits or vegetables lost their freshness if weight loss increases up to 3-10% during storage. The gamma irradiation (1.0, 1.5, and 2.0 kGy) with MAP reduced the weight loss of shiitake mushroom during storage of 8 days. The weight loss of non-irradiated shiitake mushroom kept under MAP was 4.4% after 20 days of storage. Gamma irradiation with MAP reduced the weight loss of shiitake mushroom to 2.7% throughout the whole storage [38]. Irradiation of fig samples by dose 0.5 KGy and 1 KGy kept under MAP reduced the weight loss of figs during storage of 15 days. The loss in the weight of irradiated fig samples kept under MAP was 3% during storage of 15 days. The weight loss of the control sample was 3.39% and fig samples kept under MAP was 3.12% [43].

The combined preservation techniques were proved better in the preservation of sensory attributes of food products than the single preservation technique. The sensory attributes of mushrooms (color, flavor, dark zones, gill and cap uniformity) were decreased during storage. Mushrooms treated with gamma irradiation (1.0, 1.5 and 2.0 kGy) + MAP showed better sensory properties during storage. The deterioration in color and appearance of mushrooms are associated with the browning of mushrooms tissues. Application of Irradiation with MAP inactivate the microorganisms that cause browning of mushrooms during storage [45].

Irradiated strawberry stored under active MAP retains better sensory attributes (appearance, texture, aroma and overall acceptance) than the non-irradiated strawberry samples or irradiated strawberry samples stored under air conditions. Irradiated strawberry kept under active MAP shows better appearance and texture than non-irradiated strawberry samples packed under air conditions after 7 days of storage. The sensory attributes of irradiated strawberry stored in active MAP remained acceptable even after 14 days. The score of non-irradiated strawberry kept under air conditions was below the acceptability limit for all the sensory attributes [39]. [41] reported that the treatment of Irradiation to the cut romaine kept under MAP decreased the firmness while color, flavor and visual appearance remained unaffected.

The sensory attributes (aroma, color, and flavor) of saffron treated with gamma irradiation stored under MAP score higher than the non-irradiated saffron samples kept under MAP or atmosphere packaging. The shelf life of saffron treated with irradiation (2 kGy) and stored under MAP increased from 30 days to 60 days [39].

Irradiation increase the discoloration in spices (rosemary and black pepper), MAP decreased the discoloration of spices caused by irradiation. Therefore, the MAP for spices is preferred to prevent the loss of color before the treatment of spices with irradiation [42].

The appearance and aroma of the untreated fig sample deteriorated after 5 days. Irradiated Fig samples kept under MAP received the highest score for appearance, aroma and overall acceptance than fig samples treated with irradiation or MAP only on the day 5 and 10 during storage [43]. Irradiation of meat at dose 4 kGy stored under MAP score best for all the sensory attributes than irradiated meat under air conditions. The acceptability limit for the taste and odor of a meat sample treated with a combination of irradiation (4 kGy) and MAP2 (70%/30% CO_2/N_2) was increased from 6 days to 18 -19 days. Non-irradiated meat samples kept under MAP had an acceptability limit of 9–10 days [44].

Color parameters (L^*, a^* and b^* value) of all fig samples were changed during storage at a temperature of 5 °C for 15 days. Irradiated fruits at dose 1 kGy show lower L^*, a^* and b^* values during storage than irradiated fruits at dose 1 kGy. Irradiated fruits showed a lower L^* value (lightness) for all samples than the irradiated fruits sample kept under MAP during storage. Irradiation of some fruits like figs was unable to preserve the natural color due to the oxidation of anthocyanin. A combination of irradiation by dose 0.5 kGy and MAP was found effective in preserving the color of figs. A decrease in a^* and b^* values of the irradiated sample treated kept under MAP were lower than figs samples treated with irradiation or MAP only [43]. Irradiation treated poultry meat did not have any effect on the L^* and b^* values while irradiation of poultry meat by dose 4 kGy increased the a^* values. The increase in redness of irradiated chicken meat was due to the formation of CO-myoglobin. A small effect of MAP was observed on the *L** values of poultry meat [44].

During storage of minimally processed fruits or vegetable, softening of tissue occur due to the degradation of the cell wall by the bacterial enzymes and increase the activity of endogenous enzymes. Integration of gamma irradiation + MAP reduces the softness of tissue by inactivating the enzymes. The shiitake mushrooms treated with Gamma irradiation (1.0 and 1.5 kGy) + MAP showed a higher level of firmness as compared to mushrooms sample treated with irradiation only [45].

Irradiated strawberry kept in MAP had more firmness than the irradiated fresh strawberry kept in atmosphere packaging. . The Firmness of fruits in MAP is associated with a high concentration of carbon dioxide. The reason behind the firmness of strawberry tissue due to the increasing concentration of carbon dioxide is still unknown. The firmness of fruit tissue may change due to the loss of water by respiration and transpiration [39].

The firmness of figs decreases with the increase in the storage in all irradiated figs, figs kept under MAP and figs treated with combined treatments. The firmness of figs decreased with the increase in irradiation dose. The decrease in firmness of irradiated figs was due to the degradation of pectin and destruction of cell wall caused by a high dose of irradiation. The decreased in the firmness of figs treated with irradiation by dose 2, 3 and 4 KGy was more than figs samples treated with irradiation by dose 1 KGy or untreated figs during 20 days of storage. A high dose of Irradiation also increased the softness in kiwifruit [50], peach [51] and gala apple [52]. The firmness of the figs treated with combined preservation methods (irradiation + MAP) was higher than the firmness of irradiated figs kept under air conditions. Among all the irradiated samples, figs treated with irradiation (0.5 kGy) and MAP showed the best firmness during the storage [43].

3.3. Ultraviolet treatment

3.3.1. Synergistic effect of UV-C and MAP in food preservation

Integration of UV-C and MAP are useful to increase the shelf-life food products by reducing the microbial contamination. The application of UV-C in combination with MAP or MAP individually improve the shelf life of trout fillets by reducing the mesophilic and psychotropic microbial counts. . This is because UV-C inactive the microbes present on the surface of food and unable to penetrate the depth of food products entirely. The UV-C induce changes in the biochemical composition of food products that potentially enhance the nutrient's availability and promote the growth of remaining microorganisms. The MAP contains a high concentration of carbon dioxide that reduced the microbial load of trout fillet. The bacteriostatic activity of carbon dioxide is due to its ability to penetrate the cell membrane, change in the functions of the cell membrane, inactivation of enzymes and changes in the protein properties of bacteria. MAP was effective against mesophilic bacteria while MAP+ UV-C was effective against total mesophilic and psychotropic counts **[**53]**.** The ultraviolet irradiation, and MAP extend the shelf life up to 2-5 days of tilapia fillets by reducing the growth of *S. typhimurium* and *E. coli [54]*.

Microbial load on the harvested fruits or vegetables increased sharply with time throughout the storage. An increase in the *S. Typhimurium* was seen sharply on the untreated cherry tomatoes kept at 20 °C. After 3 days of storage, reduction in the S. *Typhimurium* counts of 4.32 log CFU/g were seen on the cherry tomatoes treated with UV-C and kept under active MAP at 4 °C. After 6 days of storage, *S. Typhimurium* counts in the samples kept under active MAP were reduced to 1.05 log CFU/g as compared to untreated fresh samples kept under air conditions. After 9 days of storage, *S. Typhimurium* was decreased to 3.74 log CFU/g on the cherry potatoes treated with UV-C and kept under active MAP while the decrease in the *S. Typhimurium* counts was 5.22 log CFU/g in the cherry tomatoes without UV-C kept under MAP at 4 °C [55]. The combination of UV-C and MAP were found effective to reduce the microbial of 'Red Oak Leaf' lettuce by controlling the growth of psychotropic bacteria, coliform and yeast growth. UV-C did not have any effect on the growth of lactic acid bacteria because gram-positive bacteria show high resistance against UV-C [56].

Combined treatment UV-C+MAP reduced the initial microbial load of mesophilic, psychrophilic, enterobacteria, yeast and molds. . However, the increases in the microbial growth on the processed rocket leaves treated with UV-C and kept under MAP was less than the untreated sample. The low microbial growth on the fresh-cut rocket leaves treated with UV-C and kept under MAP during storage increase the shelf life up to 8 days. The untreated fresh-cut rocket leaves had shelf life of only 4 days due to the spoilage caused by microbes [57].

The Treatment of minimally processed pomegranate arils with UV-C and MAP reduced the growth of mesophilic, psychotropic, lactic acid and *Enterobacteriaceae* counts during storage while yeast and mold remained unaffected [58].

3.3.2. Synergistic effect on the quality attributes of food products

The antioxidant capacity of fruits or vegetables treated with UV-C + MA was higher than untreated fresh fruits or vegetables. UV-C improve the antioxidant activity by enhancing the aggregating the phenolics in tomato fruits [59]. [60] reported that UV-C treatment increases the antioxidant activity of the blueberries. UV-C improve the antioxidant activity of tomatoes by increasing the phenolic contents and flavonoids [61]. with the antioxidant of tomatoes treated with UV-C and MAP was higher as compared to untreated tomatoes. The reduction in the antioxidant activity was observed with time due to a decrease in some antioxidants like ascorbic acid. The application of UV-C inactivates the enzyme (ascorbate oxidase) responsible for the oxidation of ascorbic acid. MAP alone or in combination with UV-C decrease the oxygen responsible for the degradation of ascorbic acid. Antioxidant activity of UV-C treated fruits was significantly similar to the antioxidant activity of fruits sample treated with UV-C + MA but the antioxidant activity of fresh, control or MAP treated fruits samples were significantly different [62].

The rate of respiration of the fruits or vegetables relies on the repining level, temperature, and oxygen to carbon dioxide ratio in air. UV treatment speed up the rate of respiration in fruits and vegetables like in tomatoes [56]. The rate of respiration of tomatoes samples treated with MAP was slower as compared to the samples treated with UV-C + MAP. The MAP slows down the rate of respiration and ethylene due to the low level of oxygen (3.1%) and a higher level of carbon dioxide (11.3%). More the production of ethylene gas higher the rate of respiration. The rate of respiration of fruits sample kept under MA was slow because the ethylene gas has been eliminated through MAP films [62]. The UV-C with MAP did not have any significant effect on the rate of respiration of fresh-cut arils of pomegranate during storage [58].

Antioxidant activity was reduced in the presence of a high concentration of oxygen due to the degradation of ascorbic acid-induced by oxygen [63]. UV-C treated samples kept under MAP showed higher antioxidant activity than UV-C treated samples kept under atmosphere conditions because of a low level of oxygen assists in controlling the degradation of ascorbic acid. Higher the rate of respiration in tomatoes, the lower the antioxidant activity as respiration negatively affects the antioxidant activity. UV-C + MA increases the antioxidant activity of tomatoes samples by increasing the accumulation of phenolic acid, lowering the rate of respiration and degradation of ascorbic acid [62]. The combined treatment UV-C + MAP did not show any effect on the antioxidant activity of fresh-cut rocket leaves [57]. The antioxidant activity of treated fresh-cut rocket and untreated rocket remained unchanged at the end of storage. The application of combined treatment UV-C and MAP did not affect the antioxidant activity of minimally processed pomegranate arils during storage [58].

The weight loss of food products results in a reduction of shelf life and economic value [64]. [65] reported that Fruits or vegetable with weight loss of more than 5% lose their freshness. The improper storage condition, long storage time, high rate of transpiration and respiration are responsible for the high loss in the weight of fresh food products. The weight loss of cherry tomatoes treated with UV-C and kept under passive or active MAP was 0.45% whereas the weight loss of cherry tomatoes without UV-C was 0.64% for 9 days storage at 4 and 20 °C. there was not any large difference exist in a weight loss of all treatments [66].

High %TSS is present in fresh fruits, and it reduces overtime throughout the storage. The reason behind the decrease in TSS is the degradation of sugar. A decrease in TSS in Cherry tomato kept under MAP was reduced due to the high concentration of carbon dioxide [67]. UV+ MA treatment reduces the decrease in % TSS in tomatoes than fresh fruits or vegetable [62].

The color change of fruits is the important property for estimating the degrees of maturity. The color changes in untreated fruits are more than UV-C + MA treated fruits. The changes in the color of fruits depend on the ripening, senescence, duration of storage and conditions of storage [68]. The changes in the color of fruits treated with UV and kept under MAP or fruit samples kept under MAP is slower than the untreated sample or sample treated with UV only. The slower color changes in tomato kept under MAP is due to the presence of a low concentration of oxygen and a higher level of carbon dioxide. The main pigment responsible for the color in tomato is lycopene and its activity depends on oxygen [62].

The analysis of the external quality of cherry tomatoes was done by determining the changes in color throughout the storage. UV-C + MA treatments maintain the visual appearance of cherry tomatoes by delaying the change in the color of cherry tomatoes. The redness of cherry tomatoes increases with the increase in the lycopene throughout the storage. The change in color of untreated cherry tomatoes sample were more than cherry tomatoes treated with the combination of UV-C + MA or kept under MAP only [55]. [54] reported that MAP/UV and MAP decreased the redness and increased the yellowness of tilapia fillets during storage of 10 days. The UV-C treatment with MAP did not affect the L^*, Chroma and Hue values during the storage [57].

The firmness of fruits or vegetables is one of the important attributes that affect consumer acceptability. The firmness of fruits or some vegetables reduces during storage due to an increase in the respiration rate and enzyme activity. Fruits treated with UV+ MA had high firmness than the fruits without any treatment. A higher concentration of carbon dioxide in the MAP maintains high firmness in tomatoes. A high rate of respiration and mass loss negatively affects the firmness. The rate of respiration and weight loss was lower in tomato samples treated with UV and kept under MAP. High moisture in fruits maintains a higher firmness than the samples with low moisture content. The firmness of tomato is decreased during ripening, enzymes start to be degrading the pectin and cause softening of the cell wall. UV treatment reduced the enzyme activity responsible for the degradation of the cell wall of tomatoes. Tomato samples kept under UV+MAP showed better firmness than samples treated with UV only. The MAP contribution to improving the firmness of tomato samples was more while UV has little contribution to improve the firmness. UV-C improved the firmness of cherry tomatoes by suppressing the production of ethylene gas The higher the production of ethylene gas, the lower the firmness of tomatoes. UV+MAP treatment treatments retain the moisture of food products and removed the ethylene gas [37].

3.4. Cold Plasma

3.4.1 Synergistic effect of Cold Plasma and MAP in food preservation

Microbial flora reduced the shelf life of fresh produce by degrading the quality attributes of fresh fruits and vegetables. The consumption of food products contaminated with the toxins produced by microorganisms can harm the health of consumers. Different thermal and novel non- thermal techniques were applied to destroy the microorganisms and improve food safety [69]. The integration of cold plasma and MAP are very beneficial in term of reducing the microbial load while retaining the critical quality attributes of the strawberry. Atmospheric cold plasma reduces the mesophilic bacteria yeasts and molds on the strawberry samples kept under MAP (65 % O_2 + 16 % N_2 + 19 % CO_2) and MAP (90 % N_2 + 10 % O_2). MAP with different gases mixture has a different effect on the microorganism. MAP containing gas mixture high in N_2 (90 %) reduced mesophilic bacteria, yeasts and molds counts to 3.7 and 3.3 log whereas MAP containing gas mixture high in oxygen content O_2 (65 %) reduced the bacteria and yeast or mold to 3.1 and 3.4 logs. The reduction of mesophilic bacterial counts was more kept under MAP while the reduction of yeast counts was less [70]. Fungi are more sensitive to cold plasma as compared to mesophilic bacteria. Plasma produces UV radiation that penetrates in fungi and destroys the cell membrane of yeast by reacting with the cellular matrix inside fungi cell [71]. The rate of microbial inactivation depends on the current microbial population present on the food surface, the type of food products and its internal attributes [72]. A large population of bacteria, yeasts and molds are present on the surface of strawberry [73].

3.4.2. Synergistic effect on the quality attributes of food product

Several biochemical changes include respiration and transpiration. continue to proceed in harvested fruits and vegetables. The rate of respiration increases in harvested fruits or vegetables due to physiological stress [74]. The shelf life of fresh produce becomes limited with a high rate of respiration. The rate of respiration in fresh produce kept under MAP decrease due to a low level of oxygen and a high level of carbon dioxide. The effect of Cold plasma and MAP on the respiration rate depends on the fruits or vegetable's maturity, degree of fruits ripeness, gases percentage in the atmosphere, time, and temperature of storage [1]. It was observed that the firmness of untreated fruits or vegetable decreases during storage as tissue become soft over time. Highly perishable fruits like strawberry are soft in nature and more prone to loss of firmness. All strawberry samples treated with atmosphere cold plasma or untreated showed a decrease in firmness with 24 hours. Strawberry kept under atmosphere high in oxygen retain the best firmness whereas high nitrogen in MAP reduces the firmness [75]. Greatest retention of firmness was seen in strawberry treated with atmosphere cold plasma and kept under MAP (65 % O_2 + 16 % N_2 + 19 % CO_2). Consumer likes the bright red color of strawberry. Strawberry treated with atmosphere cold plasma and kept under MAP (65 % O_2 + 16 % N_2 + 19 % CO_2) turned brighter whereas strawberry treated with atmosphere cold plasma and kept under MAP (65 % O_2 + 16 % N_2 + 19 % CO_2) showed a decrease in brightness [76].

3.4. Pulse Electric Field

3.4.1. Synergistic effect of pulse of electric field and MAP in food preservation

The microbial load on the fresh meat surface was 4.63 log CFU/g which increase with time after 9 days microbial load was exceeded to 6 log CFU/g considered to be the microbial threshold index for the fresh meat. After 18 days, it was seen that the pork meat sample treated with the moderate electric field and kept under MAP showed low values of TVC (less than 6 logs CFU/g) during storage. MEF inactivate the microorganisms by inducing an electric field across the cell membrane which leads to the breakdown of the structure of the cell membrane [8].

3.4.2. Synergistic effect on the quality attributes

Low water-holding capacity costs the food industry millions of dollars each year. Water loss from the meat increased with the increase in storage time. [77] reported that High drip loss was recorded in 50% of products of Pork meat. Purge loss results in a decrease in the weight of meat and loss of some water-soluble proteins [78]. Different techniques were applied to suppress the drip loss of meat. Application of moderate electric field with high oxygen MAP was approved highly effective to improve the water holding capacity of meat. After 6 days unacceptable cooking losses were observed in untreated pork meat whereas cooking losses were decreased in pork meat treated with moderate electric field kept under high oxygen moderate atmosphere. The moderate electric field improves the water holding capacity by polarizing the dipoles of water molecules and arranging in the direction of the electric field within muscle tissue [79]. Polarization and arrangement of water molecules influence the compartmentalization of water [80].

Food tenderness is generally recognized as one of the most important indicators of the quality of meat. The amount of intramuscular connective tissue, the length of the sarcomere and also the proteolytic ability of the muscle affect the meat tenderness [81]. The storage of meat high in oxygen results in a decrease in tenderness and juiciness of meat whereas the storage of meat is high in oxygen atmosphere after treatment with a moderate electric field increases the softness of meat [82]. Meat treated with moderate electric field and MAP had high water holding capacity than meat samples kept under MAP only. Meat tenderness increase with the increase in the water holding capacity of meat during storage. More the water holding capacity, the higher the tenderness [8]. Combine treatment of moderate electric field and MAP retain the color of meat better than the meat sample treated with moderate electric field or MAP only. *L**, *a**, and *b** values were used for the measurement of meat color. It was observed that *L** (lightness) increased in all meat samples throughout the storage whereas *a** (redness) of meat samples treated with the moderate electric field and kept under MAP increased. Redness of meat sample kept under MAP was higher than the meat sample treated with MEF-MAP on days six and nine while lower on days 15 and 18. Meat samples kept under MAP after treatment with moderate electric field retained a brighter color of meat sample for a longer time than meat samples kept under MAP only [8].

3.5. High-Pressure Processing

3.5.1. Synergistic effect of HHP and MAP in preservation

The shelf life of meat is affected by aerobic mesophilic counts and lactic acid bacteria. The increase in aerobic mesophilic counts on the surface of meat samples kept in control air conditions was more than the meat samples kept under MAP during the storage. [83] reported that the aerobic mesophilic bacteria consume oxygen for the respiration in control air package result in high mesophilic counts at the end of storage. It was observed that the increase in lactic acid bacteria counts was similar to the meat samples kept under controlled air and MAP because LAB is a facultative anaerobic bacterium that can grow in the presence or absence of oxygen and the presence of carbon dioxide. HPP treatment of 500 MPa inactive the growth of both aerobic mesophilic bacteria and lactic acid bacteria in MAP and controlled air. A reduction of microbial counts on the meat samples treated with HPP+MAP was more than the meat samples treated with HPP and kept in controlled air conditions. Aerobic mesophilic counts on the meat samples treated with HPP and kept under air conditions and MAP were decreased to 2.60 log cfu·g^{-1} and 2.35 log cfu·g^{-1} respectively. While lab counts were under the detection limit on the meat samples treated with HPP kept under controlled air or MAP during 22 days of storage [84]. The pseudomonads. Yeasts, lactic acid bacteria (LAB) and hydrogen sulfide-producing bacteria (presumably *S. putrefaciens*) are responsible for the spoilage of salmon. The application of high pressure reduced the microbial counts of salmon to 100/g. The threshold values for the microbial contamination of salmon are 7.0–7.2 log CFU/g. After 7 days of storage, High counts of *S. putrefaciens*. were the observed result in spoilage of salmon. The application of high pressure and MAP reduced the total microbial load of the salmon. The HPP reduced the reduced growth of *S. putrefaciens* whereas MAP was effective against the LAB. The application of pressure in the range of 150 MPa-200 MPa for 30- and 60-min results in the reduction of spoilage microorganisms present on the surface of salmon [85].

3.5.2. Synergistic effect on quality attributes

The meat samples kept under air high in oxygen are more prone to oxidation. Higher the rate of lipid oxidation lowers the shelf life of meat because lipid produces undesirable flavor and off-color. The ground meat is more prone to oxidation because disruption of muscle calls exposes the unsaturated fats to oxidation. The oxidative stability of meat samples stored under the control air package after treatment with HPP was less than the meat samples kept under MAP. The presence of oxygen in a controlled air package induces oxidation of unsaturated fat of the meat samples. HPP treatment to the meat samples did not inhibit the oxidation of fat if oxygen was present in the package [84]. Oxidative stability of salmon was improved when treated with high pressure 150 MPa and kept under MAP [85]. The high intensity of HPP increases the *L** (lightness) values of salmon during storage. Application of high pressure of 50 MPa for 60 min or 200 MPa for 10 min results in the opaque color of salmon. While the application of high pressure with

MAP (50% O_2+50% CO_2) results in acceptable L^* (lightness) of salmon. The redness values of salmon samples treated with high pressure and compressed gases (50% O_2 + 50% CO_2) were decreased after 14 days of storage whereas salmon treated with high pressure and kept under vacuum packaging had acceptable values for redness after 14 days of storage [85].

IV. CONCLUSION

Nonthermal techniques have been used to inactive the microorganisms and enzymes as an alternative approach to the thermal techniques from the last two decades. Nonthermal techniques are ideal preservation techniques that extent the shelf life of food products without effecting the nutrient contents and sensory attributes. However, certain bacterial spores and enzymes showed high resistance against nonthermal techniques. Therefore, the integration of nonthermal techniques with MAP is an effective approach to inactivate all microbial spores and enzymes that cause spoilage. The combination of different non-thermal techniques like ultrasound, irradiation, ultraviolet irradiation, cold plasma, pulse electric field and high-pressure processing with MAP increase the shelf life by protecting the food products different deteriorative reactions such as oxidation, water loss, texture loss, loss of sensory attributes and accumulation of maladialdehyde.

REFERENCES

[1] Lacroix, M. and R. Lafortune, *Combined effects of gamma irradiation and modified atmosphere packaging on bacterial resistance in grated carrots (Daucus carota).* Radiation Physics and Chemistry, 2004. **71**(1-2): p. 79-82.

[2] Raso, J. and G.V. Barbosa-Cánovas, *Nonthermal preservation of foods using combined processing techniques.* 2003.

[3] Zárate-Rodríguez, E., E. Ortega-Rivas, and G.V. Barbosa-Cánovas, *Effect of membrane pore size on quality of ultrafiltered apple juice.* International journal of food science & technology, 2001. **36**(6): p. 663-667.

[4] Lado, B.H. and A.E. Yousef, *Alternative food-preservation technologies: efficacy and mechanisms.* Microbes and infection, 2002. **4**(4): p. 433-440.

[5] Ortega-Rivas, E. and I. Salmerón-Ochoa, *Nonthermal food processing alternatives and their effects on taste and flavor compounds of beverages.* Critical reviews in food science and nutrition, 2014. **54**(2): p. 190-207.

[6] Abadias, M., et al., *Growth potential of Escherichia coli O157: H7 on fresh-cut fruits (melon and pineapple) and vegetables (carrot and escarole) stored under different conditions.* Food Control, 2012. **27**(1): p. 37-44.

[7] Sandhya, *Modified atmosphere packaging of fresh produce: Current status and future needs.* LWT-Food Science and Technology, 2010. **43**(3): p. 381-392.

[8] Hu, H., et al., *Effects of the combination of moderate electric field and high-oxygen modified atmosphere packaging on pork meat quality during chill storage.* Journal of Food Processing and Preservation, 2020. **44**(1): p. e14299.

[9] Kong, F. and R. Singh, *Chemical deterioration and physical instability of foods and beverages*, in *The stability and shelf life of food*. 2016, Elsevier. p. 43-76.

[10] Mason, L.J., *Effect and control of insects, molds and rodents affecting corn quality*, in *Corn*. 2019, Elsevier. p. 213-234.

[11] Narasimha Rao, D. and N. Sachindra, *Modified atmosphere and vacuum packaging of meat and poultry products.* Food Reviews International, 2002. **18**(4): p. 263-293.

[12] Oliveira, M., et al., *Application of modified atmosphere packaging as a safety approach to fresh-cut fruits and vegetables–A review.* Trends in Food Science & Technology, 2015. **46**(1): p. 13-26.

[13] Horev, B., et al., *The effects of active and passive modified atmosphere packaging on the survival of Salmonella enterica serotype Typhimurium on washed romaine lettuce leaves.* Food Research International, 2012. **45**(2): p. 1129-1132.

[14] Charles, F., C. Guillaume, and N. Gontard, *Effect of passive and active modified atmosphere packaging on quality changes of fresh endives.* Postharvest biology and Technology, 2008. **48**(1): p. 22-29.

[15] Mullan, M. and D. McDowell, *Modified atmosphere packaging in Food Packaging Technology.* Modified atmosphere packaging, in Food and Beverage Packaging Technology, 2003.

[16] Devlieghere, F. and J. Debevere, *Influence of dissolved carbon dioxide on the growth of spoilage bacteria.* LWT-Food Science and Technology, 2000. **33**(8): p. 531-537.

[17] Parry, R., *Principles and applications of modified atmosphere packaging of foods*. 2012: Springer Science & Business Media.

[18] Severino, R., et al., *Antimicrobial effects of modified chitosan based coating containing nanoemulsion of essential oils, modified atmosphere packaging and gamma irradiation against Escherichia coli O157: H7 and Salmonella Typhimurium on green beans.* Food control, 2015. **50**: p. 215-222.

[19] Morris, C., A.L. Brody, and L. Wicker, *Non-thermal food processing/preservation technologies: A review with packaging implications.* Packaging Technology and Science: An International Journal, 2007. **20**(4): p. 275-286.

[20] Huang, H., et al., *UV-C treatment affects browning and starch metabolism of minimally processed lily bulb.* Postharvest Biology and Technology, 2017. **128**: p. 105-111.

[21] Wu, T., et al., *Ultrasonic disruption of yeast cells: underlying mechanism and effects of processing parameters.* Innovative Food Science & Emerging Technologies, 2015. **28**: p. 59-65.

[22] Dehghani, M.H., *Effectiveness of ultrasound on the destruction of E. coli.* American journal of environmental sciences, 2005. **1**(3): p. 187-189.

[23] Caleb, O.J., et al., *Modified atmosphere packaging of pomegranate fruit and arils: a review.* 2012. **5**(1): p. 15-30.

[24] Abdalhai, M.H., et al., *Effect of ultrasound treatment prior to vacuum and modified atmosphere packaging on microbial and physical characteristics of fresh beef.* Journal of Food and Nutrition Research, 2014. **2**(6): p. 312-320.

[25] Fan, K., M. Zhang, and F.J.U.s. Jiang, *Ultrasound treatment to modified atmospheric packaged fresh-cut cucumber: influence on microbial inhibition and storage quality.* 2019. **54**: p. 162-170.

[26] Zhang, X.-t., et al., *Effect of Combined Ultrasonication and Modified Atmosphere Packaging on Storage Quality of Pakchoi (Brassica chinensis L.).* Food and Bioprocess Technology, 2019. **12**(9): p. 1573-1583.

[27] O'donnell, C., et al., *Effect of ultrasonic processing on food enzymes of industrial importance.* Trends in food science & technology, 2010. **21**(7): p. 358-367.

[28] Barbagallo, R., M. Chisari, and G. Spagna, *Enzymatic browning and softening in vegetable crops: studies and experiences.* Italian journal of food science, 2009. **21**(1).
[29] Huang, G., et al., *Effects of ultrasound on microbial growth and enzyme activity.* Ultrasonics sonochemistry, 2017. **37**: p. 144-149.
[30] Zhang, F., et al., *Effects of ultrasonic treatment combining modified atmosphere package on quality and physiological changes of Psidium guajava during postharvest storage.* Journal of Southern Agriculture, 2017. **48**(3): p. 493-498.
[31] Brummell, D.A. and M.H. Harpster, *Cell wall metabolism in fruit softening and quality and its manipulation in transgenic plants*, in *plant cell walls*. 2001, Springer. p. 311-340.
[32] Cansino, N., et al., *Ultrasound processing on green cactus pear (Opuntia ficus indica) juice: physical, microbiological and antioxidant properties.* 2013. **4**(9).
[33] Bhat, R., et al., *Sonication improves kasturi lime (Citrus microcarpa) juice quality.* 2011. **18**(6): p. 1295-1300.
[34] Putnik, P., et al., *Effects of modified atmosphere, anti-browning treatments and ultrasound on the polyphenolic stability, antioxidant capacity and microbial growth in fresh-cut apples.* 2017. **40**(5): p. e12539.
[35] Li, N., et al., *Improved postharvest quality and respiratory activity of straw mushroom (Volvariella volvacea) with ultrasound treatment and controlled relative humidity.* Scientia Horticulturae, 2017. **225**: p. 56-64.
[36] Ahn, H.-J., et al., *Combined effects of irradiation and modified atmosphere packaging on minimally processed Chinese cabbage (Brassica rapa L.).* Food Chemistry, 2005. **89**(4): p. 589-597.
[37] Chervin, C. and P. Boisseau, *Quality maintenance of "ready-to-eat" shredded carrots by gamma irradiation.* Journal of Food Science, 1994. **59**(2): p. 359-361.
[38] Jiang, T., et al., *Effect of integrated application of gamma irradiation and modified atmosphere packaging on physicochemical and microbiological properties of shiitake mushroom (Lentinus edodes).* Food Chemistry, 2010. **122**(3): p. 761-767.
[39] Jouki, M. and N. Khazaei, *Effects of low-dose γ-irradiation and modified atmosphere packaging on shelf-life and quality characteristics of saffron (Crocus Sativus Linn) in Iran.* Food Science and Biotechnology, 2013. **22**(3): p. 687-690.
[40] Lacroix, M., et al., *The influence of atmosphere conditions on Escherichia coli and Salmonella typhi radiosensitization in irradiated ground beef containing carvacrol and tetrasodium pyrophosphate.* Radiation Physics and Chemistry, 2004. **71**(1-2): p. 61-64.
[41] Prakash, A., et al., *Effects of low-dose gamma irradiation on the shelf life and quality characteristics of cut romaine lettuce packaged under modified atmosphere.* Journal of Food Science, 2000. **65**(3): p. 549-553.
[42] Kirkin, C., et al., *Combined effects of gamma-irradiation and modified atmosphere packaging on quality of some spices.* Food Chemistry, 2014. **154**: p. 255-261.
[43] Waghmare, R.B. and U.S. Annapure, *Integrated effect of radiation processing and modified atmosphere packaging (MAP) on shelf life of fresh fig.* Journal of food science and technology, 2018. **55**(6): p. 1993-2002.
[44] Chouliara, E., et al., *Combined effect of irradiation and modified atmosphere packaging on shelf-life extension of chicken breast meat: microbiological, chemical and sensory changes.* European Food Research and Technology, 2008. **226**(4): p. 877-888.
[45] Jiang, T., et al., *Influence of UV-C treatment on antioxidant capacity, antioxidant enzyme activity and texture of postharvest shiitake (Lentinus edodes) mushrooms during storage.* Postharvest Biology and Technology, 2010. **56**(3): p. 209-215.
[46] Owureku-Asare, M., et al., *Effect of gamma irradiation treatment and storage on physico-chemical, microbial and sensory quality of minimally processed pineapple (Ananas comosus).* Current Journal of Applied Science and Technology, 2014: p. 2752-2761.
[47] Sadler, G.D. and P.A. Murphy, *pH and titratable acidity*, in *Food analysis*. 2010, Springer. p. 219-238.
[48] Wani, A., et al., *Effect of gamma-irradiation and refrigerated storage on the improvement of quality and shelf life of pear (Pyrus communis L., Cv. Bartlett/William).* Radiation Physics and Chemistry, 2008. **77**(8): p. 983-989.
[49] Fan, X. and J.P. Mattheis, *1-Methylcyclopropene and storage temperature influence responses of 'Gala'apple fruit to gamma irradiation.* Postharvest Biology and Technology, 2001. **23**(2): p. 143-151.
[50] Kim, J.-H., et al., *The combined effects of N2-packaging, heating and gamma irradiation on the shelf-stability of Kimchi, Korean fermented vegetable.* Food control, 2008. **19**(1): p. 56-61.
[51] McDonald, H., et al., *Commercial scale irradiation for insect disinfestation preserves peach quality.* Radiation Physics and Chemistry, 2012. **81**(6): p. 697-704.
[52] Fernandes, Â., et al., *Effects of gamma irradiation on physical parameters of Lactarius deliciosus wild edible mushrooms.* Postharvest Biology and Technology, 2012. **74**: p. 79-84.
[53] Lázaro, C., et al., *Effects of ultraviolet light on biogenic amines and other quality indicators of chicken meat during refrigerated storage.* Poultry Science, 2014. **93**(9): p. 2304-2313.
[54] Lázaro, C.A., M.L.G. Monteiro, and C.A. Conte-Junior, *Combined Effect of Modified Atmosphere Packaging and UV-C Radiation on Pathogens Reduction, Biogenic Amines, and Shelf Life of Refrigerated Tilapia (Oreochromis niloticus) Fillets.* Molecules, 2020. **25**(14): p. 3222.
[55] Choi, D.S., et al., *The combined effects of ultraviolet-C irradiation and modified atmosphere packaging for inactivating Salmonella enterica serovar Typhimurium and extending the shelf life of cherry tomatoes during cold storage.* Food packaging and shelf life, 2015. **3**: p. 19-30.
[56] Allende, A. and F. Artés, *Combined ultraviolet-C and modified atmosphere packaging treatments for reducing microbial growth of fresh processed lettuce.* LWT-Food Science and Technology, 2003. **36**(8): p. 779-786.
[57] Gutierrez, D.R. and S.d.C. Rodriguez, *Combined effect of UV-C and modified atmosphere packaging for keeping antioxidant compounds and extend to shelf-life of fresh-cut rocket leaves.* International Journal of New Technology and Research, 2017. **3**(6).
[58] López-Rubira, V., et al., *Shelf life and overall quality of minimally processed pomegranate arils modified atmosphere packaged and treated with UV-C.* Postharvest biology and technology, 2005. **37**(2): p. 174-185.
[59] Srilaong, V. and Y. Tatsumi, *Changes in respiratory and antioxidative parameters in cucumber fruit (Cucumis sativus L.) stored under high and low oxygen concentrations.* Journal of the Japanese Society for Horticultural Science, 2003. **72**(6): p. 525-532.
[60] Perkins-Veazie, P., J.K. Collins, and L. Howard, *Blueberry fruit response to postharvest application of ultraviolet radiation.* Postharvest Biology and Technology, 2008. **47**(3): p. 280-285.
[61] Castagna, A., et al., *Effect of post-harvest UV-B irradiation on polyphenol profile and antioxidant activity in flesh and*

peel of tomato fruits. Food and bioprocess technology, 2014. **7**(8): p. 2241-2250.
[62] Vunnam, R., et al., *Physico-chemical changes in tomato with modified atmosphere storage and UV treatment.* Journal of food science and technology, 2014. **51**(9): p. 2106-2112.
[63] Rojas-Graü, M.A., et al., *The use of packaging techniques to maintain freshness in fresh-cut fruits and vegetables: a review.* International Journal of Food Science & Technology, 2009. **44**(5): p. 875-889.
[64] Kraśniewska, K., et al., *The use of pullulan coating enriched with plant extracts from Satureja hortensis L. to maintain pepper and apple quality and safety.* Postharvest Biology and Technology, 2014. **90**: p. 63-72.
[65] Koide, S. and J. Shi, *Microbial and quality evaluation of green peppers stored in biodegradable film packaging.* Food Control, 2007. **18**(9): p. 1121-1125.
[66] Vunnam, R., et al., *Physico-chemical changes in tomato with modified atmosphere storage and UV treatment.* Journal of food science and technology, 2014. **51**: p. 2106-2112.
[67] Akbudak, B., et al. *The effect of harpin treatment on storage of cherry tomato cv. Naomi*. in *IV International Conference on Managing Quality in Chains-The Integrated View on Fruits and Vegetables Quality 712*. 2006.
[68] Moneruzzaman, K., et al., *Effect of stages of maturity and ripening conditions on the physical characteristics of tomato.* American Journal of Biochemistry and Biotechnology, 2008. **4**(4): p. 329-335.
[69] Kim, H.Y., et al., *Gas temperature effect on reactive species generation from the atmospheric pressure air plasma.* Plasma Processes and Polymers, 2013. **10**(8): p. 686-697.
[70] Misra, N., et al., *Nonthermal plasma inactivation of food-borne pathogens.* Food Engineering Reviews, 2011. **3**(3-4): p. 159-170.
[71] Park, B.J., et al., *Sterilization using a microwave-induced argon plasma system at atmospheric pressure.* Physics of Plasmas, 2003. **10**(11): p. 4539-4544.
[72] Fernandez, A., E. Noriega, and A. Thompson, *Inactivation of Salmonella enterica serovar Typhimurium on fresh produce by cold atmospheric gas plasma technology.* Food Microbiology, 2013. **33**(1): p. 24-29.
[73] Jensen, B., et al., *Characterization of microbial communities and fungal metabolites on field grown strawberries from organic and conventional production.* International journal of food microbiology, 2013. **160**(3): p. 313-322.
[74] Rico, D., et al., *Extending and measuring the quality of fresh-cut fruit and vegetables: a review.* Trends in Food Science & Technology, 2007. **18**(7): p. 373-386.
[75] Wszelaki, A. and E. Mitcham, *Effects of superatmospheric oxygen on strawberry fruit quality and decay.* Postharvest Biology and Technology, 2000. **20**(2): p. 125-133.
[76] Misra, N., et al., *Cold plasma in modified atmospheres for post-harvest treatment of strawberries.* Food and bioprocess technology, 2014. **7**(10): p. 3045-3054.
[77] Stetzer, A. and F. McKeith, *Benchmarking value in the pork supply chain: Quantitative strategies and opportunities to improve quality Phase 1.* Savoy (IL): American Meat Science Association, 2003.
[78] Huff-Lonergan, E. and S.M. Lonergan, *Mechanisms of water-holding capacity of meat: The role of postmortem biochemical and structural changes.* Meat science, 2005. **71**(1): p. 194-204.
[79] Rayat, K. and F. Feyzi, *Influence of external electric field on the polarity of water droplets in water-in-oil emulsion phase transition.* Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2011. **375**(1-3): p. 61-67.
[80] Stadnik, J. and Z.J. Dolatowski, *Influence of sonication on Warner-Bratzler shear force, colour and myoglobin of beef (m. semimembranosus).* European Food Research and Technology, 2011. **233**(4): p. 553.
[81] Rawdkuen, S., M. Jaimakreu, and S. Benjakul, *Physicochemical properties and tenderness of meat samples using proteolytic extract from Calotropis procera latex.* Food chemistry, 2013. **136**(2): p. 909-916.
[82] Lund, M.N., et al., *High-oxygen packaging atmosphere influences protein oxidation and tenderness of porcine longissimus dorsi during chill storage.* Meat Science, 2007. **77**(3): p. 295-303.
[83] Patsias, A., et al., *Combined effect of freeze chilling and MAP on quality parameters of raw chicken fillets.* Food Microbiology, 2008. **25**(4): p. 575-581.
[84] Lerasle, M., et al., *Combined use of modified atmosphere packaging and high pressure to extend the shelf-life of raw poultry sausage.* Innovative Food Science & Emerging Technologies, 2014. **23**: p. 54-60.
[85] Amanatidou, A., et al., *Effect of combined application of high pressure treatment and modified atmospheres on the shelf life of fresh Atlantic salmon.* Innovative Food Science & Emerging Technologies, 2000. **1**(2): p. 87-98.