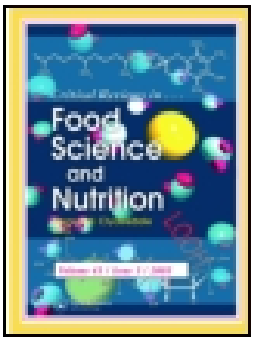

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Recent development in the application of alternative sterilization technologies to prepared dishes: A review

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ABSTRACT
Sterilization is one of the most effective food preservation methods. Conventional thermal sterilization commonly used in food industry usually causes the deterioration of food quality. Flavor, aroma, and texture, among other attributes, are significantly affected by thermal sterilization. However, demands of consumers for nutritious and safe dishes with a minimum change in their original textural and sensory properties are growing rapidly. In order to meet these demands, new approaches have been explored in the last few years to extend the shelf-life of dishes. This review discusses advantages and disadvantages of currently available physical sterilization technologies, including irradiation (eg. Gamma rays, X-rays, e-beams), microwave and radio frequency when used in prepared dishes. The preservation effect of these technologies on prepared dishes are normally evaluated by microbiological and sensory analyses.

KEYWORDS
Physical sterilization; prepared dishes; application

1. Introduction

Nowadays, prepared dishes including fresh vegetables, seafood and some read-to-eat dishes becoming popular due to its convenience to cook and eat. However, preservation of prepared dishes that could have a long shelf life, with a high nutrition content and good tastes as well, has always been a challenge to processors.

Sterilization is the method to inactivate microorganisms and has been one of the most effective ways to preserve food. And thermal sterilization is commonly used in food industry. Conventional thermal sterilization method frequently means high-temperature treatment of at least 121°C of wet heat to inactivate spoilage microorganisms including spore (Deák 2014). This process can achieve the goal of extending shelf life, but usually leads to serious quality losses of the products. Sensory qualities (eg. color, taste), rheological properties and changes in the food components are the main indicators of acceptable foods after processing. Ali et al. (Sreenath, Abhilash et al. 2009) reported that the textures of sardines packed in aluminum cans were impaired by thermal processing. The texture of Indian mackerel also deteriorated after thermal sterilization. Kong et al. (Kong, Tang et al. 2008) reported heating significantly changed the quality attributes of Salmon muscle, including color, shear force, cook loss, and shrinkage. The conventional sterilization can also be limited by the condition of packaging process which could lead to recontamination of products. Consequently, the food sterilized by traditional high-temperature heating may not be accepted by consumers as they pursue for the nutritious, safe and healthy food along with good appearance (Norton and Sun 2008). It is necessary to find better thermal or non-thermal methods to improve the quality of product over traditional sterilization. And the best result of sterilization should be that microorganism are quickly and effectively killed with the minimum impact on the quality of food as well as meeting the requirements of product.

This review will highlight the potential use of electro-magnetic technologies applied to prepared dishes as an alternative technology to traditional processing. It contains six sections, introducing several technologies which has a potential or good performance on the prepared dishes. It reviews the irradiation sterilization, a non-thermal process with ionizing radiation, the microwave sterilization, a thermal process with microwave radiation and the radio frequency sterilization, a thermal process the same as microwave. The potential for industrial application on prepared dishes of these three technologies is clearly demonstrated via examples at the laboratory scale research, shown on Table 1.

2. Alternative technologies

The quest for new technologies in food processing opens the opportunity to produce significantly higher quality foods, while at the same time reducing costs and processing times. Additionally, alternative technologies can address a number of issues that conventional technologies cannot. There are three alternative technologies introduced in this review. And the main differences of three technologies from conventional thermal sterilization are listed on Table 2.

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Table 1. Application of irradiation, microwave and radio frequency in processing of prepared food products.

Technology	Condition	Products	Effect	Reference
Irradiation				
γ-irradiation	10 kGy	*Bulgogi* sauce, ready-to-eat stir fry chicken dices, freeze-dried *miyeokguk*;	sterilization	(Chen, Cao et al. 2016)
	1 kGy	pre-cut mixed vegetables		(Feliciano, de Guzman et al. 2017)
	25 kGy	Ready-to-eat chicken breast *Adobo*		(Feliciano, De Guzman et al. 2014)
	gamma-irradiated at 25 kGy and −70°C	Ready-to-cook *Bibimbap*, ready-to-eat *Kimchi*		(Song, Park et al. 2009, Park, Song et al. 2012)
X-rays	2.0 and 1.0 kGy, respectively	Chicken breast fillets and shell eggs	sterilization	(Robertson C B. 2006)
	2.0 kGy	Ready-to-eat smoked mullet		
	0.6 kGy	Raw tuna fillets		(Mahmoud, Nannapaneni et al. 2016)
	0.75 kGy	Ready-to-eat shrimp, oysters		(Mahmoud 2009, Mahmoud. 2009)
e-beams	1.5 kGy	Iberian dry-cured ham, dry beef, and smoked tuna	sterilization	(Cambero, Cabeza et al. 2012)
	10 kGy	chili shrimp paste		(Cheok, Sobhi et al. 2017)
	10 kGy	Beef jerky		(Kim, Chun et al. 2010)
	0.95 kGy and 2.04kGy, respectively	Chicken steaks and hamburgers		(Carcel, Benedito et al. 2015)
Microwave	915 MHz	Salsa (a Mexican sauce); pre-packaged carrots; sweet purple potato; chicken meat	Pasteurization Sterilization	(Sung and Kang. 2014, Peng, Tang et al. 2017)
Radio frequency	27.12 MHz	Meat lasagna; scrambled egg; prepared carrots; prepared *Nostoc sphaeroides*	Sterilization	(Luechapattanaporn K. 2005, Wang, Luechapattanaporn et al. 2012, Xu, Zhang et al. 2017, Xu, Zhang et al. 2017)
Combined methods				
γ-irradiation and heating	heating at 100°C for 30 min andγ-irradiation at 17.5 kGy	*Gochujang* Sauce		(Jae-Nam Park and Lee. 2010)
e-beams and addition of extract	Adding 1.0% leek extract and e-irradiation at 3 kGy	Pork jerky	sterilization	(Kang, Kim et al. 2012)
microwave and addition of ZnO	2450 MHz microwave (400 W 150 s) heating along with 0.02 g kg^{-1} ZnO nanoparticle addition.	Caixin	sterilization	(Liu Q. 2014)
γ-irradiation and active coating	0.4 kGy	ready-to-eat broccoli floret		(Ben-Fadhel, Saltaji et al. 2017)

2.1 Irradiation and mechanism

Food irradiation is a non-thermal process that inactivates microorganism by exposing the food to a certain amount of ionizing radiation which mainly includes gamma rays, X-rays and electron beams (Farkas, Ehlermann et al. 2014). Some properties of three irradiations are shown as Table 3.

The goal of food irradiation is to make microorganisms inactivated and extend shelf life. It is known now that irradiation can directly or indirectly transfer its own energy to food to achieve the goal. The irradiation effects result due to the non-specific collision of photons of radiation with the atoms in the molecules of the microorganisms, causing the lethal damage of DNA and RNA chains (Tahergorabi, Matak et al. 2012). The indirect effects can also occur due to the free radicals generated during water radiolysis, which contribute to damage of nucleic acid, protein and enzyme. It should be noted that some environmental factors such as oxygen, water activity, and pH of food can affect the efficiency of irradiation (Lim, Hamdy et al. 2003, Sommers 2012, Roberts 2014).

Table 2. Selected sterilization methods for the comparative analysis.

Methods	Physical field	Thermal or non-thermal
Conventional thermal method	No	Thermal
Irradiation	Electromagnetic	Non-thermal
Microwave	Electromagnetic	Thermal
Radio frequency	Electromagnetic	Thermal

2.2 Microwave and mechanism

Microwaves have a frequency range between 300 MHz and 300 GHz. In USA, the use of microwave radiation is regulated by the Federal Communications Commission (Salazar-Gonzalez, San Martin-Gonzalez et al. 2012), and only two frequencies are used commercially, 915 and 2450 MHz.

Microwave sterilization involves primarily two mechanisms, dielectric and ionic.

Under the action of the microwave magnetic field, the microbial bodies have higher temperature than the surrounding fluid, resulting in destruction and death (Guo, Sun et al. 2017). The second major mechanism of sterilization is that ions in the food generates heat under the influence of the oscillating electric field (Barbosa-Canovas, Medina-Meza et al. 2014), leading to the loss of normal metabolism, growth and reproduction capacity of microorganisms.

2.3 Radio frequency and mechanism

RF heating is less commonly used than MW heating in food processing. This was discussed in two reviews mentioned in Section 1 (Zhao, Flugstad et al. 2000, Piyasena, Dussault et al.

Table 3. The difference of three sources of ionizing radiation.

	Gamma Rays	X-rays	Electron Beams
Power source	Radioactive isotope	Electricity	Electricity
Properties	Photons (1.25 MeV) $\lambda = 1 \times 10^{-12}$ m	Photons $\lambda = 3 \times 10^{-10}$ m	Electrons Mass $= 9.1 \times 10^{-31}$ kg
Emissions	Isotropic (direction cannot be controlled)	Forward peaked	Unidirectional

2003). Radio frequency ranges between 300 kHz and 300 MHz, and among the range, only 13.56, 27.12 and 40.68 MHz can be applied to industry (Fellows 2000).

The mechanism of RF are similar to microwave due to the thermal and non-thermal effects. The killing of bacteria using RF was owing to heat generated on the substrate. And non-heat associated mechanisms mainly included improper protein folding, damages to the integrity of the membrane or DNA damages (Jiao, Tang et al. 2014, Xu, Zhang et al. 2017). RF heating achieves quicker heating times than conventional heating and all parts of the product heat at the same rate (Zhang, Lyng et al. 2004, Zhang, Lyng et al. 2004, Brunton, Lyng et al. 2005, Lyng, Zhang et al. 2005).

2.4 Advantages and disadvantages of technologies

According to the existing researches, irradiation has been used in many fields, such as agriculture, food processing and so on. Irradiation has a potential to be widely used in food industry mainly for due to unique advantages over conventional sterilization methods of food, such as highly effective and efficient, versatile and energy-saving (Roberts 2014). According to the calculation of IAEA (International Atomic Energy Agency), refrigerated energy-consumption is 90kW · (h / t), pasteurized disinfection 230kW · (h / t), thermal sterilization 300 kW · (h / t), irradiation 6.3kW · (h / t), and irradiation pasteurization only 0.76 kW· (h / t), which means that irradiation can save energy consumption up to 70% to 90% (Thore A 1975, Shamsuzzaman, Goodwin et al. 1989). However, it also has some disadvantages: expensive equipment; a taste of irradiation when operating improperly.

Different from irradiation, microwave and radio frequency are all thermal processes. Microwave radiation directly penetrates the material which contributed to volumetric heat generation in the material, resulting in high-energy efficiency and lower heating times (Zhu, Kuznetsov et al. 2007, Salazar-Gonzalez, San Martin-Gonzalez et al. 2012). Due to its outstanding features, it has been widely applied to food processing which includes thawing, heating, blanching, pasteurization, sterilization, cooking, drying and frying (Venkatesh and Raghavan 2004). However, the disadvantage of microwaves cannot be ignored. It always failed in the uniform temperature distribution (Ryynänen, Tuorila et al. 2001), and always resulted in “edge overheating effect” (Resurreccion, Tang et al. 2013), which limits its application. Related studies have been done to overcome this problem (Tang, Mikhaylenko et al. 2008). And researches showed that by using water as an intermediate step to heat the food products some of the drawbacks of the technology such as non-uniform heating and edge effects can be resolved (Chang, Xu et al. 2011, Barbosa-Canovas, Medina-Meza et al. 2014).

RF energy has the same features as microwave, but has a deeper penetration with a longer wavelengths and more uniform heating area, which make it more efficient (Marra, Zhang et al. 2009) and suitable for large food trays (Wang, Tang et al. 2003). Also, RF has a limitation of potential inconsistent heating profile, which lead to hot and cold spots within the products that can affect the safety and quality (Schlisselberg, Kier et al. 2013).

In summary, each technology has its own advantages and disadvantages, which are listed on Table 4. According to the

Table 4. The advantages and disadvantages of each technology.

Technologies	Definition	Advantages	Disadvantages
Conventional thermal sterilization	Conventional thermal sterilization method frequently means high-temperature treatment of at least 121°C of wet heat to inactivate spoilage microorganisms including spore (Deák 2014).	Rendering food sterile and extend shelf-life	Serious quality losses of the products with long processing time
Irradiation	A non-thermal process that inactivates microorganism by exposing the food to a certain amount of ionizing radiation which mainly includes gamma rays, X-rays and electron beams (Farkas, Ehlermann et al. 2014).	A cold process; highly effective and efficient; easy to control; low energy-consumption and cost	Expensive equipment; a taste of irradiation when operate improperly
Microwave	A thermal process with microwave radiation of frequency range between 300 MHz and 300 GHz, and 915 and 2450 MHz can be used commercially (Sung and Kang 2014).	Shorter heating time to reduce the negative thermal impact on products; efficient	Heating uniformity
Radio frequency	A thermal process with radio frequency between 300 kHz and 300 MHz, and among the range, only 13.56, 27.12 and 40.68 MHz can be applied to industry (Fellows 2000).	A deeper penetration with a longer wavelengths and more uniform heating area compared with microwave; more efficient and suitable for large food trays (Wang, Tang et al. 2003)	Hot and cold spots within the products that can affect the safety and quality

target of products processing, a suitable technology can be chosen.

3. Application in prepared dishes

3.1 Irradiation and application

As a non-thermal sterilization technology, food irradiation has a good ability of sterilization, and also can maintain the quality of food. Although it has been applied to food industry for many years and over 50 countries have use it, irradiated food cannot be accepted completely by consumers (Park, Song et al. 2012). Many people think that irradiated food have potential danger for health and take it for granted. In fact, many studies have proved it safety and relative regulations have published many years ago. In 1981, a Joint Expert Committee on Food Irradiation (Joint 1981) was established by the WHO/IAEA/FAO. And the most important conclusion drawn was that the irradiation applied to food is proved no healthy threat and no nutritional or microbiological problems with the dosage of less than 10 kGy. After that, the WHO Technical Report 890 on High Dose Irradiation showed that food irradiated to any dose appropriate for the technological objective is safe and nutritionally adequate and high-dose irradiated foods are as safe as foods sterilized by thermal processing (Group 1999). Consequently, it is no doubt that high-dose irradiated food is not a threat to people's health.

3.1.1 Gamma-irradiation and dosage selection

As for the doses of irradiation, it mainly depends on the target of products processing. Generally, low to moderate doses (generally accepted as below 10 kGy) do not guarantee sterility (the complete absence of viable micro-organisms). Such doses are considered useful for reducing microbial load and thus improving food safety. Such doses will often also extend shelf-life but by amounts measured in days.

Song, Kim et al. (2009) studied the effect the efficacy of gamma and electron beam irradiation of the food-borne pathogens including *Listeria monocytogenes, Staphylococcus* aureus, and *Vibrio parahaemolyticus* in *Bajirak jeotkal* (8% salt). The results suggested that a low dose irradiation can improve the microbial quality and reduce the risk from the food-borne pathogens.

In a study by Park J G. (2012), total bacterial growth, the viscosity, and the sensory properties of *Bulgogi* sauce were compared between sterilization with gamma irradiation (0, 10, 20, 40 kGy, respectively) and autoclave thermal treatment during storage at 35°C for 90 days. The data showed that the dose of gamma irradiation above 10 kGy can assure *Bulgogi* microbial safety but totally changed its sensory properties and texture. Thus a gamma irradiation of 10 kGy was a good choice for *Bulgogi* sauce preservation.

Chen, Cao et al. (2016) reported that a suitable dose of γ-irradiation is effective to maintain the original quality of ready-to-eat stir fry chicken dices with hot chili (FCC). The microbial safety, sensory quality and protein content of the samples gamma irradiated at 10, 20, 30 and 40 kGy were investigated during storage for one year at 25°C. The results on Table 5 showed that the dose of 10 and 20 kGy were both suitable dose for FCC.

Kang, Park et al. (2016) did some research on the half-dried seafood products which can be contaminated with norovirus. Results indicated that more than 7 kGy of gamma irradiation could be effective in reducing MNV-1 titers by more than log10 PFU/mL (>90%), and color and sensory evaluation did not change.

Feliciano, de Guzman et al. (2017) studied the gamma-irradiated brown rice, ready-to-eat pre-cut fresh fruits, and mixed vegetables. It was concluded that the shelf life of brown rice irradiated at 1 kGy can be extended from three to five months and the sensory acceptability was not affected. During the pre-cut mixed vegetables (carrots, lettuce, and cucumber) tests, the dose of 1 kGy was also found to be effective enough to significantly reduce the level of microbial contamination and prolonged the shelf-life up to 4 days. Thus, the irradiated food can achieve the acquirement of microbiological safety.

Doses of 25 kGy and above are considered to render food sterile and with proper packaging and storage will be safe to consume indefinitely, though quality may be compromised. An interesting Annex of the WHO Technical Report 890 on High Dose Irradiation gives three case studies of practical experience with high-dose irradiation, namely diets for persons with compromised immune systems, astronauts and shelf-stable foods now available to the public in South Africa (Group 1999). And relative researches have been done for recent years.

Feliciano, De Guzman et al. (2014) processed ready-to-eat (RTE) chicken breast *Adobo* with pathogen-free to be provided to immuno-compromised patients. The samples were prepared, vacuum-packed and stored in chilled condition (4°C) overnight before gamma-irradiation at 25 kGy. The samples without irradiation was as a control. All samples were evaluated by microbiological safety, nutritional adequacy and sensory characteristics. The results showed that high-dose gamma rays (25 kGy) combined with chilling and vacuum-packaging treatment was effective to maintain the nutrition of *Adobo* and meet the demand of pathogen-free, and extended shelf-life to 60 days.

Yun, Lee et al. (2012) tried to sterile ready-to-eat chicken breast by high-dose (above 30 kGy) gamma irradiation used in special food. The samples was irradiated at 40 kGy, 5 kGy, non-irradiated as a control, and then stored at 4°C for 10 days. Microbiological, chemical, and sensory analyses were conducted on day0 and day10. It was included that samples irradiated at 40 kGy had a better microbiological quality than 5 kGy on day 10, but it had an off-odor which influenced its sensory characteristics.

Park, Song et al. (2012) reported that ready-to-cook *Bibimbap*, as a space food, treated by 25kGy gamma irradiation at −70°C along with 0.1% of vitamin C added and vacuum-packaging got a higher score than treated by irradiation only. Also, after treatment in the way above, the products meet the requirements of Russian Institute of Bio-medical Problems for shelf life.

Song, Park et al. (2009) also do the same research on ready-to-eat *Kimchi*, a traditional Korean fermented vegetable. The prepared *Kimchi* samples were added into 0.01% of calcium lactate and 0.3% of vitamin C, packaged and heated at 70°C for

Table 5. Effects of γ-irradiation on microbes and sensory characteristics of FCC. (Chen, Cao et al. 2016).

Dose (kGy)	Total aerobic bacteria (log CFU/g)	Yeast and molds (log CFU/g)	Color	Flavor	Texture	Overall acceptance
0	1.40 ± 0.13	ND[c]	8.0 ± 0.7	8.0 ± 0.6^{a}	$8.0 \pm 0.5^{a,b}$	8.2 ± 0.5^{a}
10	ND	ND	8.3 ± 0.2	8.2 ± 0.3^{a}	$7.9 \pm 0.7^{a,b}$	8.0 ± 0.5^{a}
20	ND	ND	8.4 ± 0.2	8.2 ± 0.5^{a}	$8.0 \pm 0.4^{a,b}$	8.0 ± 0.5^{a}
30	ND	ND	8.3 ± 0.3	7.8 ± 0.4^{a}	$7.7 \pm 0.5^{a,b}$	$7.8 \pm 0.4^{a,b}$
40	ND	ND	8.1 ± 0.5	7.2 ± 0.6^{b}	7.5 ± 0.8^{b}	7.3 ± 0.6^{b}

[a-b]Values with different letters within a column differ significantly (po0.05).
[c]ND, not detectable within a detection limit < 1.0 log CFU/g.

30 min. Then the samples were cooled and gamma-irradiated at 25 kGy at $-70°$C. The results showed that the product are suitable to serve as space food.

3.1.2 X-rays and application

X-rays was used less commercially than gamma rays but also have ability of sterilization. Shin, Lee et al. (2014) combined the efficacy of X-rays and electron beam on the Bologna sausage and results showed that high-energy X-ray irradiation has the potential to replace gamma or electron beam irradiation. Robertson, Andrews et al. (2006) evaluated the effect of X-rays irradiation on sterilization of ready-to-eat, vacuum-packaged smoked mullet. The samples were irradiated at 0, 0.5, 1.0, 1.5, and 2.0 kGy and the population of microorganism were measured, sensory quality evaluated during storage. It proved that X-rays was efficient in sterilizing smoked mullet without changing the its flavor.

As produce consumption has increased, a significant increase in the number of foodborne disease outbreaks and illnesses, associated with fresh produce, has also been reported (Beuchat 1990, Mahmoud 2009). For the better determine the parameters of X-rays, some researches are conducted on the bacteria causing the food deterioration, such as Shigella, Salmonella, Escherichia coli O157:H7, Listeria monocytogenes (Beuchat 1990).

Mahmoud, Nannapaneni et al. (2016) reported that the raw tuna fillets inoculated *Salmonella enterica* treated by X-rays can improve its quality. To better understand the efficiency of X-rays, the sample were irradiated by X-rays at 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 kGy, respectively and then relative data were analyzed. The result showed that the *Salmonella enterica* population was significantly ($p < 0.05$) reduced with the increase of dosage and samples treated at 0.6 kGy X-ray was under the detected limit ($<$1.0 log CFU g^{-1}).

Mahmoud (2009) did the research on ready-to-eat shrimp. The life-threatening bacteria related to shrimp was inoculated to shrimp and then all samples were treated with 0.1, 0.2, 0.3, 0.5, 0.75, 1.0, 2.0, 3.0 and 4.0 kGy X-ray, respectively. The data indicated that it is a good choice for shrimp to be treated by X-rays and the dose of 2.0, 3.0 and 4.0 kGy X-ray can reduce its microorganism load to less than the detectable limit.

Mahmoud, Chang et al. (2015) did an experiment on chicken breast fillets and shell eggs, inoculated by *Salmonella*, to determine the efficacy of X-rays. The samples were irradiated at 0.0, 0.1, 0.5, 1.0, and 2.0 kGy. The results indicated that the 0.5 kGy X-ray treatment significantly reduced the *Salmonella* population by 1.9 and 3.0 log reduction on chicken breast meat and shell egg samples, respectively, with greater than a 6 log CFU reduction being achieved with 2.0 and 1.0 kGy X-ray for chicken and shell eggs, respectively.

3.1.3 Electron beam and application

Electron beam irradiation is a low cost, environment friendly, and time effective alternative to the traditional thermal decontamination technology (Lung, Cheng et al. 2015), which make it possible to be applied in preservation of dishes. The efficiency of e-beams irradiation is influenced by irradiation dose, food composition and microbial species (Moosekian, Jeong et al. 2012).

In the study of Cheok, Sobhi et al. (2017), he studied the effectiveness of electron beams on the Chili shrimp paste by evaluating the physicochemical qualities and microorganisms decontamination. After the treatment of electron beams and heating respectively, irradiated retained 23 volatile compounds of 24 and heating only 19.

Cambero, Cabeza et al. (2012) studied the proper dose of e-beams for three ready-to-eat intermediate-moisture vacuum-packed products: Iberian dry-cured ham, dry beef, and smoked tuna. Samples were prepared and treated with an industrial E-beam at 1 to 3 kGy. The microbial safety and sensory quality were valued, and they concluded that the treatment of 1.5 kGy can assure the safety of these products and had a very long storage period.

Kim, Chun et al. (2010) did the similar research. The beef jerky samples were irradiated at doses of 0, 1, 3, 5, and 10 kGy and stored at 20°C for 60 d. The total amount of aerobic bacteria was measured on day 0, 15, 30, 60, respectively. Also, some sensory indexes were evaluated, such as Hunter color values, appearance, and odor. The data indicated that the populations of total aerobic bacteria were significantly decreased with increasing dosages of electron beam irradiation. In particular, total aerobic bacteria populations could be significantly decreased at 10 kGy of irradiation, resulting in improved microbial safety without altering the quality of beef jerky during storage.

Carcel, Benedito et al. (2015) tried to model the effect of e-beam treatment on the safety, shelf-life and sensory attributes of two poultry products, steaks and hamburgers, and to optimize the radiation treatment. The irradiation doses employed were 0, 1, 2, 3, and 4 kGy. The optimization results obtained for hamburger samples showed that the optimum irradiation dose was 2.04 kGy. This value was found optimum in relation to combined effect on the changes in the appearance, odor and aroma with the increase in the irradiation dose. As for steaks, 0.95 kGy was a relatively proper dosage.

3.1.4 Irradiation combined with other treatment

Combining irradiation with other treatments, has been proposed as an additional option for enhancing product safety and quality.

In order to find a good combination method and better preserve *Gochujang* (Korean Fermented Red Pepper Paste) Sauce, Jae-Nam Park and Lee (2010) heated all samples in a 100°C water bath for 30 min, and then γ-irradiated at 12.5, 15, 17.5, 20, and 22.5 kGy. It was concluded that combination treatment of γ-irradiation at 17.5 kGy after heating at 100°C for 30 min (HT-IR) had a best performance in sensory characteristics as well as nutritional value.

Kang, Kim et al. (2012) studied the combined effect of electron-beam irradiation and addition of leek on pork jerky. Samples were added with 1.0% leek extract and irradiated by electron-beam at 0, 0.5, 1, 2, 3, 4 kGy doses. Microbial population was counted. The results showed that pork jerky irradiated at 3 kGy in combination with leek extract did a better performance in microbial safety than the control samples only irradiated by e-beams.

Zhu, Mendonca et al. (2009) reported that the treatment of irradiation with 2% sodium lactate and 0.1% sodium diacetate added to ready-to-eat turkey breast rolls was efficient in ensuring microbial safety and maintaining the sensory quality. As for the dose of irradiation, 1.0 kGy was a best choice.

Ben-Fadhel, Saltaji et al. (2017) studied the effect of the active coating combined with γ-irradiation on the four pathogens (Escherichia coli O157:H7, Listeria monocytogenes, Salmonella Typhimurium and Aspergillus niger) and then applied to the broccoli floret. The results showed that there is synergistic effect between active coating and γ-irradiation on ready-to-eat broccoli floret and extend the shelf life stored at 4°C.

To better store ready-to-eat Idli, a steam-cooked breakfast food item consumed in India, Mulmule, Shimmy et al. (2017) uses electron beams to make microorganism sterilized, finding that 2.5 kGy was not effective enough to extend shelf life and 7.5 kGy could affect the sensory qualities. However, the low dosage of electron beams along with thermal processing can balance the relationship between shelf life and sensory qualities.

3.2 Microwave and application

Microwave heating, as an alternative conventional heating method, is used in both domestic and industry. The heat can be rapidly transferred between microwaves and food products, which overcomes the drawback of conventional thermal processes. Therefore, the microwave heating time can be significantly reduced to retain superior product quality (Zhang 2014). Qi Biao et Biao. (2013) reported that the effect of microwave sterilization was close to that of high temperature sterilization, but the quality change was little. The efficiency of microwave processing are influenced by many factors, including treatment time, microwave frequency, food product parameters (mass, size, density, geometry), dielectric properties (e.g. dielectric constant and dielectric factor) and localization of food (Tang, Feng et al. 2002, Ahmed and Ramaswamy 2004). The dielectric properties which indicates the dissipation of electromagnetic energy to heat is affected by the moisture and salt content of the food product (Jha, Narsaiah et al. 2011).

The application of microwave on the prepared dishes are mainly divided into two parts, vegetables and meat products. And the effects of microwave sterilization on food quality mainly include microbiological and sensory attributes.

Peng, Tang et al. (2017) used the gellan gel model food to simulate the pre-packaged carrots in microwave processing, and determine the heating pattern and cold/hot pot distribution for better uniformity. After the hot water and microwave treatment respectively, lower $\triangle$E values was found in the carrot samples processed by microwave, which indicated a better color retention.

In the study of Liu Q. (2014), Caixin, a popular vegetable in China, was treated at the best sterilization condition of 2450 MHz microwave (400 W 150 s) heating along with 0.02 g kg^{-1} ZnO nanoparticle addition, showing a good effect both on color and texture.

Xu, Chen et al. (2016) reported that sweet purple potato processed by the combination of microwave and steam-cooking, preserved the antioxidant activity compounds better and also reduced processing time. As for the meat products, the inactivation of food-borne pathogen may be the first goal to achieve.

Zeinali T. (2015) inoculated *Listeria monocytogenes* to chicken meat and then to evaluate the effect of microwave. And the data showed there was no bacterium detected when samples were treated more than 60 seconds. Akbar and Anal (2015) found that *Salmonella* still existed in the ready-to-eat chilled poultry meat during storage. And it is efficient to reheat for more than 90s by microwave to eliminate the target bacteria (10^6–10^7 CFU/g)

For the better application of microwave technology, many model foods have been used to explore the dielectric properties of microwave processing, for instance, rice model food systems to simulate medium moisture food products (Auksornsri, Tang et al. 2018) and mashed potato with gellan gum to high moisture food (Bornhorst, Tang et al. 2017), and then match the dielectric properties of real foods to determine the heating pattern and cold/hot spot, which is beneficial for microwave sterilization process development. Also, more work need to establish food model for various real food.

3.3 Radio frequency and application

RF heating is a novel technology to replace conventional heating technologies as post-heat treatment decontamination technologies of packaged and non-packaged products (Sosa-Morales, Valerio-Junco et al. 2010), including some food dishes. The efficacy of RF heating is affected principally by the dielectric properties of the product, as well as geometry shape and product position (Orsat, Bai et al. 2004, Marra, Zhang et al. 2009). The dielectric properties are mainly influenced by the moisture content and the presence of additives, sometimes affected by temperature.

Jian Wang et al. (Wang, Tang et al. 2009) researched the dielectric properties of liquid whole eggs and liquid egg whites during heated by radio frequency and microwave. The dielectric properties of eggs were measured at 27 and 40 MHz RF frequencies and 915 and 1800 MHz microwave frequencies. It was concluded that ionic conductivity was a dominant factor determining the dielectric loss behavior of egg products at radio frequencies, whereas dipole water molecules played an increasing role with an increase in microwave frequencies.

The application of radio frequency heating was mainly studied for vegetables and meat. Xu, Zhang et al. (2017) evaluated the effect of ZnO nanoparticles combined RF heating on the prepared carrots, comparing with the ZnO nanoparticles and RF heating alone. The total CFU of prepared carrots did not reach the limit of 1000 CFU/g after 60 days storage. Also, RF heating at 20 min maintain good color, hardness and carotenoids content. Thus, ZnO nanoparticles combined RF heating have a synergistic effect to extend the shelf life of prepared carrots.

Making sure the microbial safety, flavor is also an important indicator to evaluate the effect of sterilization. Xu, Zhang et al. (2017) also did research on prepared *Nostoc sphaeroides* by RF, comparing with high pressure steam sterilization. The data from electronic nose showed that the RF sterilization caused much less flavor degradation compared to HP steam sterilization.

Wang, Luechapattanaporn et al. (2012) studied feasibility of using radio-frequency (RF) energy to thermally process highly heterogeneous foods in large containers as shelf-stable products, meat lasagna as a study example. Dielectric properties of beef, mozzarella cheese, noodles, and sauce were determined between 1 and 1800 MHz and from 20 to 121°C. Computer simulations were conducted to evaluate the influence of the dielectric properties of each food component on the electric field distribution and heating pattern during RF heating. The results showed that the vastly different temperature dependent loss factors among different food components at 27.12 MHz did not cause major non-uniform heating inside heterogeneous foods.

Byrne B. (2010) studied pork luncheon meat, inoculated with Bacillus cereus and *Clostridium perfringens vegetative cell* and spore cocktails in maximum recovery diluent(MRD), cooked by radio frequency heating. Samples were RF cooked (500 W) under circulating water at 80°C for 33 min using the RF oven and polyethylene cell as described by Zhang, Lyng et al. (2004). After 33 min the RF power was turned off and the samples were held in the circulating water at 80°C for a further 2 min. The study showed that for RF microbial challenge studies, adjustment of product formulation prior to MRD addition was critical to ensure a similar composition to the normal product and a true picture of microbial inactivation.

4. Conclusion remarks

The sterilization technologies mentioned in this review appear to be a good alternative to conventional thermal treatment. Irradiation, including gamma-irradiation, X-rays and e-beams, has a good effect when used in prepared dishes, including some special dishes for patients and astronauts. Microwave and radio frequency are mainly used to heat dishes, and have the potential for dishes preservation. When combined different methods along with proper conditions, they showed better results. However, some limitation of each technology need to be researched and improved for further commercial application. More work is needed to make sure that these technologies could provide true sterilization or shelf life extension of food. Then the next, combination of sterilization methods and packages should be reviewed as well.

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