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Research progress on microbial control techniques of prepared dishes

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ABSTRACT

Prepared dishes are popular among consumers due to their convenience, but microorganisms in dishes have the potential to cause spoilage and even lead to foodborne illnesses, rendering microbial control a critical step in production. This paper reviews microbial control techniques commonly used in prepared dishes, including conventional thermal techniques; novel thermal processing, including microwave (MW) and radio frequency (RF) heating; and non-thermal treatment, such as high-pressure processing (HPP) and irradiation. In addition, it summarizes the applications of these techniques in prepared dishes and analyzes factors affecting microbial inactivation, providing guidance for the optimization of these techniques. These technologies are compared in terms of technical characteristics, commercial applicability, the dish types for which they are suitable, etc. Traditional thermal treatment is currently the main processing method used for the industrial microbial control of prepared dishes, while other novel processing technologies have their own characteristics. MW has poor penetration ability, RF is suitable for dishes with a regular shape and consistent thickness, HPP (generally 300–600 MPa) is unsuitable for dishes containing air bubbles, and low-dose irradiation ($<$ 10 kGy) is preferred only for the pasteurization of prepared dishes due to food safety concerns. Finally, the challenges and countermeasures associated with their application in prepared dishes are discussed. Further studies and continuous improvements of microbial control techniques are of great significance to produce safe and high-quality prepared dishes.

1. Introduction

Current definitions of prepared dishes, prepared food, ready-to-eat dishes, and ready-to-eat food are vague, having no clear distinctions or definitions. Among these, prepared food and prepared dishes are more widely used at present, where the former concerns a broad range of products that can be classified into different categories according to the type of raw materials, distribution conditions, degree of processing, and consumption methods [1], as shown in Table 1. Some papers equate prepared dishes with prepared food, but it is preferable to regard prepared dishes as a kind of prepared food. Prepared dishes include industrially produced traditional dishes that belong to the category of finished products and can be eaten either directly or after heating, such as Kung Pao Chicken, Shredded Pork with Fish, Mapo Tofu, Korean Bibimbap. Prepared dishes with regional characteristics are popular among

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Table 1
Classification of prepared food.

Classification standard	Category	
Raw material	Livestock	
	Aquatic products	
	Vegetables	
	Grains	
	Edible mushrooms	
Circulation condition	Frozen storage (< -18℃)	
	Cold storage (0–10℃)	
	Room temperature	
Degree of processing	Raw material	
	Semi-finished product	
	Finished product	Prepared dish
		Staple food
		Snack food
		Sauces and cured products
Edible method	Ready to eat	
	Ready to heat	
	Ready to cook	
	Ready to serve	

consumers due to their unique flavor, often requiring a variety of raw materials for cooking and having a complicated production process. Regardless, most are eaten immediately after cooking to ensure better taste and flavor.

Nowadays, as food processing technology has undergone rapid development, many traditional dishes have been commercially produced. As such, prepared dishes are in high demand in Europe, North America, and Asia. For instance, China is the largest contributor to the prepared dishes industry [2]; currently, there are more than 70,000 prepared dishes companies in China. With strong support for the government, the scale of China's prepared dishes market has been growing steadily over the past 3 years, worth approximately 58 billion USD in 2022, representing a year-on-year growth of 21.3 %. The market penetration rate of prepared dishes in both the United States and Japan exceeds 60 %, while it is only 10–15 % in China, which means prepared dishes in China have a greater development potential. As such, in 2026, China's prepared dishes industry is expected to evolve into the trillion-dollar market [3].

Several factors have contributed to the development of the prepared dishes industry, the first of which is the expansive consumer market. With the accelerating pace of life, an increasing number of people have no time or interest in cooking, and a lack of cooking skills is also a hindrance. Rising incomes have also led to a change in consumption attitudes; despite the relatively higher cost compared to homemade dishes, prepared dishes remain popular among consumers due to their enhanced convenience. A survey by Future Market Insights shows that 46 % of consumers like the idea of pre-packaged food and 31 % prefer to eat pre-packaged food [4]. In addition, the emergence of the central kitchen concept has altered the operation mode of restaurants, as choosing prepared dishes can accelerate cooking speed and shorten consumers' total eating time. A popular restaurant, Saizeriya sells prepared dishes, requiring only 10 min to complete 15 dishes, greatly improving the efficiency of food delivery, improving the customer flow rate. Many companies have set up their own central kitchens to produce prepared dishes and distribute them to various affiliated stores. This not only reduces costs and increases efficiency but also helps maintain consistency in product quality. Furthermore, advancements in food processing technology and improvements in the food production chain both ensure the large-scale production of prepared dishes, with the development of logistics, cold chains, and supply channels also opening a broad space for the prepared dishes industry.

However, microorganism have become an important factor in the safety of prepared dishes, with the proliferation of spoilage microorganisms damaging the quality of prepared dishes, resulting in wasted resources and economic losses. Pathogenic microorganisms, including *Escherichia coli*, *Salmonella*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Bacillus cereus*, may induce foodborne diseases, leading to such symptoms as abdominal pain, diarrhea, nausea, and vomiting [2,5]. This poses a significant threat to consumer health. In addition, some drug-resistant bacteria can enter the human body through prepared dishes. Guo et al. [6] investigated drug-resistant *E. coli* in prepared dishes in Singapore and found that 24 of 99 isolated strains of *E. coli* were resistant to one or more antimicrobial drugs. These antibiotic-resistant bacteria may be transmitted to humans through food, which is a threat to human health. There are multiple steps in the production and consumption of prepared dishes, and the sources of pathogenic bacteria in these dishes are closely related to raw and auxiliary materials, production processes, the production environment, operators, storage conditions, and more [7]. Due to their typically neutral pH, complex composition, high water activity, and rich nutrient content, prepared dishes provide favorable conditions for microorganism growth and reproduction. Therefore, inactivation of microorganisms is of great significance to ensure the safety of prepared dishes.

Despite the rapid growth of the prepared dishes industry and the importance of microbial control in protecting consumer health, the microbial control of prepared dishes has received little attention. Current research mostly focuses on the control of microorganisms in prepared foods, such as ham and fresh-cut fruits and vegetables. In addition, there are only two reviews with high relevance to the microbial control of prepared dishes published in the past 5 years [2,8]. Yu et al. [2] focus on the application of physical fields in processing prepared dishes and do not specifically focus on microbial control. Meanwhile, Huang et al. [8] investigate the application of physical sterilization technologies to prepared dishes using only irradiation, microwave (MW), and radio frequency (RF). In this study, we comprehensively summarize five common microbial control techniques for prepared dishes, including the conventional thermal technique, MW, RF, high-pressure processing (HPP), and irradiation. We also analyze factors affecting the microbial control effect of each technology in detail, which is of great significance to optimizing microbial control techniques. In addition, these technologies were compared in terms of technical characteristics, commercial applicability, and suitable dish types, which could provide effective guidance in the production of prepared dishes.

2. Microbial control techniques for prepared dishes

2.1. Conventional thermal technique

The conventional thermal technique primarily utilizes water or steam as a heating medium, relying on heat convection or conduction to heat food from the periphery to the interior, resulting in the elimination of microorganisms. Based on the above heat transfer mode, cold spots in conventional thermal processing are always situated at the geometric center of the product. Consequently, it is essential to monitor the cold spot's temperature and ensure it reaches the target temperature during processing. High-temperature thermal treatment alters the structure of proteins, causes denaturation and loss of the original functions of enzymes and membrane proteins in microorganisms, and destroys the structure of nucleic acids, affecting the growth and reproduction of microorganisms [9].

In the conventional thermal technique, D, Z, and F_0 values are widely used to assess the efficacy of microbial control, where the D value represents the time needed to decrease the microbial population by one logarithmic unit under specific conditions, Z indicates the temperature adjustment required to either increase D by tenfold or decrease it to 1/10, and F_0 the time needed to eliminate a specific number of microorganisms at 121°C [10]. These are important parameters for predicting microbial inactivation during thermal treatment, but the main problem with the conventional thermal technique is that it causes great damage to food quality, including degradation of heat-sensitive nutrients and loss of flavor and texture [11,12]. To reduce the damage from thermal treatment to food quality, many improvements have been made in recent years. Such technologies as ultra-high temperature (UHT) instantaneous processing and variable retort temperature (VRT) processing have been developed, the former of which utilizes temperatures of 130–150°C to process food briefly (2–8 s), whereas the dynamic temperature changes in VRT aim to minimize temperature differences between the interior and surface of the food [13–15]. These enhanced thermal techniques ensure food safety while preserving the nutritional value and sensory quality of foods more effectively Table 2.

2.1.1. Applications of the conventional thermal technique in prepared dishes

Currently, conventional thermal processing is still the most widely used microbial control method for prepared dishes. Rajkumar et al. [16] determine that Goat Meat Curry could be commercially sterilized with an F_0 value of 12 min, and the finished product achieved a high sensory score ranging from 8.0 to 8.4, out of 9.0. In the thermal retort processing of Samgyetang, no bacteria were detected with an F_0 value of 8 min and the finished product quality was still in the acceptable range, though a larger F_0 value would produce adverse effects on the quality, such as increasing lipid oxidation and significantly reducing the proportion of polyunsaturated fatty acids [17]. The main defect of the conventional thermal technique is its potential to cause severe nutritional loss and sensory changes in dishes. Yet, a variety of improvements have been made to reduce the damage caused by the conventional thermal technique to food quality. On the one hand, focusing on the technique itself, UHT and VRT reduce the damage of heat to food by adjusting the temperature or time. On the other, different techniques can be combined with the conventional thermal technique to complement each other, such as microwave-assisted or pressure-assisted thermal treatment. Furthermore, the emergence of novel equipment has also improved the microbial control effect of the conventional thermal technique. For example, machines can stir foods during thermal processing to improve the uniformity of heat transfer, and a direct steam-air injection system can directly transfer the latent heat of steam to the fluid, improving heat utilization efficiency. Yet, a computer simulation is a powerful tool to optimize thermal processing, as heat exchange simulation models can predict the heat transfer of the microbial killing process and image analysis techniques visualize food quality during this procedure [18–20], reducing the costs required to optimize thermal treatments.

2.1.2. Factors affecting the conventional thermal technique

Temperature and time are crucial parameters of conventional thermal processing. Xie et al. [21] examine the flavor of Water-boiled Salted Duck treated under different conditions using gas chromatography–liquid chromatography. The results reveal a significant increase ($P < 0.05$) in the contents of aldehyde, ketone, and furan after treatment at 121°C for 20 min. In contrast, thermal treatment at 95°C for 40 min or 85°C for 50 min had a lesser effect on the flavor of the duck. This was attributed to the lower temperature, reducing the degree of lipid oxidation, and the subsequent increase in aldehyde and ketones. However, an insufficient temperature cannot guarantee the microbial safety of prepared dishes. Although both conditions of 84°C for 35 min and 95°C for 30 min were able to maintain the odor of Dezhou-braised Chicken without overdoing the flavor, *Bacillus* and *Clostridium* still had strong activity after treatment at 84°C for 35 min, but they were completely inactivated by thermal treatment at 95°C for 30 min [22]. Shortening the heating time can better maintain sensory quality, and UHT processing is primarily based on this principle. With a constant F_0 value of 5 min, Tang et al. [23] examine the quality change in Sweet and Sour Carp at four temperatures (110, 115, 121, and 130°C), where the highest treatment temperature (130°C) and shortest processing time (18 min) could improve the texture of the fish and the color and rheological properties of the sauce, and the dishes also achieved a higher sensory score, though no significant difference ($P > 0.05$) was observed between the product and control groups.

Table 2
Applications of the conventional thermal technique to prepared dishes.

Prepared dish	Treatment temperature (°C)	Treatment time (min)	F_0 (min)	Microbial control effect	Quality change	Ref.
Mackerel Fishballs	121	57 63 69	21 25 32	An F_0 of 32 ensured the microbiological safety of dishes	Mackerel Fishballs treated with an F_0 of 32 had the highest score of all sensory attributes	[12]
Goat Meat Curry	121	22	12	An F_0 of 12 sterilized dishes commercially	Dishes had acceptable sensory qualities and their sensory scores were 8.0–8.4 out of 9.0	[16]
Samgyetang	121	60 80	8 29	Both total plate counts (TPCs) and anaerobic bacteria were completely deactivated	An F_0 of 8 min improved the acceptability of Samgyetang, but increasing F_0 promoted lipid oxidation	[17]
Water-boiled Salted Duck	85 95 121	50 40 20	—	—	Treatments at 85°C and 95°C had a lesser effect on flavor components compared to 121°C	[21]
Dezhou-braised Chicken	84 95 121	35 30 20	—	TPC was below 1 log CFU/g after all three treatments, *Bacillus* and *Clostridium* were only active in 84°C-treated samples	Treatments at 84°C and 95°C could better maintain the fresh odor of the product compared to 121°C	[22]
Sweet and Sour Carp	110 115 121 130	86 40 23 18	5	The dishes were commercially sterilized under four processing conditions	Dishes treated with 130°C received the highest sensory attribute score compared to other groups	[23]
Imitation Shrimp Curry	121	(Steam-air retort) 36 (Water immersion) 44	11 10	—	Steam-air treatment shortened processing time and improved the quality of Imitation Shrimp Curry	[24]
Fresh Cabbage Borsch	111 116 121 131	78 45 40 23	3	—	Treatment at 116°C could better maintain the quality of Fresh Cabbage Borscht	[25]
Rogan Josh	121	—	7 8 9 10 11	TPCs were undetectable after all treatments	Rogan Josh treated with an F_0 of 9 had the highest overall acceptability	[26]
Bulgogi	121	15	—	TPCs in Bulgogi were below the detection limit at 35°C for 90 d of storage	Significant deterioration in the hardness, texture, and taste of Bulgogi ($P < 0.05$)	[31]
Pulav	118	—	2 3 4 5 6	An F_0 of 3 deactivated both TPC and coliforms	—	[32]

Conventional thermal treatment varies terms of heating form, whether hot air, steam, or water bath heating. The heat penetration characteristics of prepared dishes under different heating methods differ, resulting in different microbial control effects. During thermal treatment at 121℃, the heating rate of Imitation Shrimp Curry was faster under steam-air treatment, requiring a total process time of only 36 min. In comparison, the water immersion treatment required 44 min, though the quality of the Shrimp Curry under steam-air treatment was superior [24]. The packaging style of the prepared dishes is also a factor affecting thermal treatments. Different packages have different heat transfer coefficients, which can produce different effects on prepared dishes under similar processing conditions. Kirse-Ozolina et al. [25] assess the effect of using a doypack (Polyethylene terephthalate/Aluminum/Polyamide/Chlorinated polypropylene; PET/AL/PA/CPP) or glass jar on the quality of Fresh Cabbage Borscht when pasteurized. The Borscht in the doypack after thermal treatment had a higher a value and lower b and L values, meaning the color was redder and better preserved. Meanwhile, the Borscht in the glass jar generated a caramel flavor after pasteurization, though the sensory quality was reduced. Moreover, the doypack product had a fast heat transfer rate, which could shorten the pasteurization cycle two-fold, reduce energy consumption, and improve economic efficiency. Shah et al. [26] also find that the doypack form (Polyethylene terephthalate/Aluminum/Chlorinated polypropylene/Biaxially oriented Polyamide; PET/AL/CPP/BOPA) in thermal processing not only reduced energy consumption but also improved the sensory properties of food. Parameters must be adjusted for products with different package sizes during thermal treatment, as an increased product size decreases heat penetration and increases the time to reach the target temperature [27]. Ignoring the effect of package size on thermal processing may result in the excessive or insufficient killing of microorganisms.

2.1.3. *Challenges of applying the conventional thermal technique to prepared dishes*

Despite its limitations in preserving the sensory and nutritional quality of food compared to new microbial control techniques, such as MW, RF, and HPP, the conventional thermal technique remains extensively employed in food processing, especially for sterilization treatment, as we have few options at the current stage. This can be attributed to its extensive developmental history, maturity in equipment technology, foundational role as a reference for evaluating the effectiveness of other microbial control techniques, and the trust it garners from both businesspeople and consumers [28]. Therefore, the conventional thermal technique still plays a significant role in the microbial control of food [29,30]. Conventional thermal technique usually needs copious amounts of water, resulting in wasted resources. Despite the appearance of some new devices, they are primarily focused on liquid foods and less used in prepared dishes. In addition, because a temperature of 121℃ for 30 min can achieve effective sterilization, most operations choose this condition without any adjustments. In the future, the development of appropriate treatment protocols for different prepared dishes and microbial types is necessary.

2.2. *Microwave*

MW is an electromagnetic wave with a frequency range of 300 MHz–300 GHz, widely used in food processing [33]. To avoid interference with other applications, the U.S. Federal Communications Commission (FCC) specifies MW frequencies available in the food industry as between 915 MHz and 2450 MHz [34]. However, commercial MW systems for microbial control are mainly manufactured in developed countries, including by the OMAC, Berstorff, Top's Food, and Micvac companies, along with Washington State University. All these systems contain heating, holding, and cooling modules, and some have preheating, equilibration, and decompression sections [35]. MW is a thermal treatment technology that uses alternating electric fields to induce the constant collision of polar molecules to generate heat and kill microorganisms [36,37]. In addition, MW can selectively heat microorganisms to a higher temperature than surrounding food materials. This phenomenon may be attributed to the fact that microorganisms have good dielectricity, with an electrical charge on their surfaces, and they are more capable of converting electrical energy into heat [38]. Some studies have also claimed that MW has non-thermal effects when killing microorganisms, but no consistent conclusions have been reached, and currently, MW treatment is developed mainly based on its thermal effects. Because MW can penetrate food and convert to heat inside, it has a faster heating rate and less heat loss compared to the conventional thermal technique, a property allowing MW to preserve better the sensory attributes of prepared dishes Table 3.

2.2.1. *Applications of MW to prepared dishes*

MW has been used to pasteurize prepared dishes, such as beef, chicken, and potatoes. For example, Hague et al. [39] apply MW to cooked beef and find the count of *Clostridium sporogenes* in the MW treated group to be nearly 4 log count/cm^2, which is lower than that in the control group after 70 d of storage at 10℃. Another study compared the effects of a water bath, RF and MW on the shelf life and quality of Braised Beef, and MW had the highest microbial killing effect, with a 2.13-log CFU/g reduction in TPC and the best product flavor, and its shelf life was extended to 35 d; in comparison, water bath and RF could only extend shelf life by about 20 d [40], possibly because MW has fastest heating rate and it may induce further chemical reactions, such as the Maillard reaction, and the degradation of amino acids, resulting in enhanced flavor. Yang et al. [41] also find that retort processing produced 2-pentylfuran, which destroyed the flavor of Duck, while Duck treated with MW does not contain this compound, and MW treatment increased the relative content of 1-octen-3-ol, a characteristic compound of mushroom aroma. MW does not destroy muscle bundles and can also induce protein cross-linking to form a dense network structure, reducing damage to the texture. However, some studies have shown that MW treatment has a worse impact on the texture of prepared dishes than conventional thermal processing, which may be related to the selection of MW conditions and food substrates.

MW treatment has problems of inhomogeneity and the existence of cold spots, which may lead to microbial residues. Thermal-assisted MW treatment is an effective method to improve heating uniformity by microwaving packaged food in hot water, alleviating

Table 3
Applications of MW in prepared dishes.

Prepared dish	Power (W)	Time (s)	Microbial control effect	Quality change	Reference
Beef	700	20	The spore count of *Clostridium sporogenes* in the MW treated group was nearly 4 log count/cm^2 lower than that in the control group after 70 d of storage at 10°C	—	[39]
Braised Beef	800	120	After MW treatment, TPC decreased by 2.13 log CFU/g, and the shelf life of Braised Beef was extended by 35 d at 37°C	The flavor of Braised Beef was better than that in the control group, but the texture, taste, and color were damaged	[40]
Duck	7000	144	Duck treated with MW achieved commercial sterility	The flavor and muscle bundles of MW-treated duck were better than with general retort heating.	[41]
Potato Omelet	300 450 600 800	80 60 40 40	All treatments reduced *Salmonella* by at least 4 log CFU/g	—	[45]
Hongsu Chicken	1400 1750 2100	300 180 120	Treatment at 1750 W for 180 s reduced TPC by 6.5 log CFU/g	Sensory score of Hongsu Chicken treated with 1750 W for 180 s was close to control group	[47]
Fried Rice	700	180 240	Treatment at 700 W for 180 s reduced *B. cereus* vegetative cells and spores by more than 3 log CFU/g, respectively	—	[48]
Fried Rice	—	600	MW-assisted thermal pasteurization had good control of yeasts, molds, and pathogenic bacteria in Fried Rice, leading to an extended shelf life from 5 d to 42 d at 7°C	MW treatment significantly affected the texture of eggs and green onion ($P < 0.05$)	[54]

the problem of overheating at the edges, because water can regulate the product temperature [42]. Ensuring good temperature distribution of the product during MW treatment and locating cold and hot spots are essential to ensuring microbial control efficacy, so it is necessary to obtain a real-time temperature distribution in product. A single-mode cylindrical cavity with a self-regulated power-supply system was designed to ensure thorough and uniform microbial inactivation in foods, whereas MW power varied with the temperature of the sample to achieve precise temperature control and maintain the product temperature at the target level [43]. Developing model foods and establishing simulation models can thus better predict the effects of MW on microorganisms and food quality, providing a reference for the design of commercial MW processes [44,45].

2.2.2. Factors affecting MW

MW frequency affects the depth of penetration, and the penetration depth decreases as frequency increases. As well, the MW penetration depth in food is bout 8–22 cm at 915 MHz and only 3–8 cm at 2450 MHz [46]. However, MW power and processing time also affect microbial inactivation, the former of which determines the intensity of the electric field, where a greater output power means a stronger electric field, causing molecules to move violently and hasten the heating rate. With a long processing time, food can absorb more MW energy and enhance the microbial killing effect. For instance, the MW treatment of Hongsu Chicken reduced the TPC from 7.56 log CFU/g to about 1 log CFU/g, requiring 5 min at 1400 W. In addition, at 1750 W, the treatment time was reduced to 3 min, and with an increase to 2100 W, it took only 2 min to achieve the same microbial control effect [47]. Treatment at 700 W for 3 min could reduce *B. cereus* vegetative cells and spores in Fried Rice by 3.41 log CFU/g and 3.02 log CFU/g, respectively, and the MW killing effect is enhanced when the processing time is extended to 4 min [48].

The dielectric property of food is an important factor affecting MW processing, where the dielectric constant and dielectric loss factor characterize the ability to store and convert electromagnetic energy, respectively, and they are important parameters for calculating power absorption and penetration depth [49]. Dielectric property is related to the composition of food, where a generally higher moisture content or water activity is associated with a larger dielectric loss factor, but it is not an absolute linear correlation. For instance, Guan et al. [50] found that an increase in moisture content from 81.6 % to 87.8 % had no significant effect on both the dielectric constant and dielectric loss factor at 915 MHz, but an increase in salt content from 0.8 % to 2.8 % raised the dielectric loss factor from 27.1 to 52.4 at 20°C. Furthermore, the dielectric property is also affected by frequency and temperature. In a study conducted by Brinley et al. [51], the dielectric constant of potato puree decreased by about 10 when the temperature increased from 15°C to 145°C, while the dielectric loss factor increased quadratically with an increasing temperature. This may be due to the increase in ionic conductivity at elevated temperatures, altering the dielectric loss factor. Furthermore, the shape of food significantly influences the distribution of MW energy, where rectangular food leads to microwave aggregation in the corners, resulting in corner heating, and spherical food causes MWs to aggregate in the center, leading to faster heating of the central part.

2.2.3. Challenges of applying MW to prepared dishes

The use of MW to control microorganisms in food is well established, and a commercial MW system is available. Some commercial MW devices for the microbial control of prepared dishes have emerged. For example, Nanjing Yongqing Food Development of New and High Technology Co., Ltd., has developed tunnel-type MW microbial control equipment for prepared dishes, the capacity of which ranges from 100 kg/h to 1000 kg/h and the price from 10,791 to 83,009 USD [52]. Although the equipment is not overly expensive, its application to prepared dishes is still in the initial stages, possible because of the lack of energy consumption analyses, so it is difficult to assess the cost of MW processing [53]. There are some other problems with the application of MW to prepared dishes. On the one hand, there are too many types of prepared dishes, and a prepared dish usually contains multiple ingredients [54]. Determining how to categorize dishes reasonably and according to shape, dielectric properties, or composition and then develop corresponding MW processes for dishes with distinct characteristics remains a challenge. In addition, the poor penetration capacity of MW means it struggles to handle dishes with large thicknesses, which is a limitation for large-scale and high-efficiency production. The common packaging for prepared dishes includes aluminum foil composite packaging, but aluminum has a shielding effect on electromagnetic waves and is unsuitable for MW processing. The development of packaging suitable for MW processing should be continued in the future.

2.3. Radio frequency

RF is an alternating electromagnetic wave with a frequency of 3 kHz–300 MHz, and to avoid interference with communication, only specific frequencies (13.56, 27.12, and 40.68 MHz) are permitted for industrial, scientific, and medical (ISM) purposes in most countries [8]. for instance, the frequency commonly used in food processing is 27.12 MHz [55]. RF is similar to MW, both of which are examples of dielectric heating. RF equipment generally includes parallel electrode plates, with the sample placed between two plates during processing. Under the influence of alternating electric fields, RF acts on the sample in the direction perpendicular to the plates, making ions move in the direction with an opposite charge. During this period, the electric field changes constantly, causing ion oscillation and dipole molecule rotation within the food. These ions and dipole molecules continue to move at a high speed, and the constant friction generates heat, promoting the death of microorganisms [56,57]. Some studies also report that RF exhibits a non-thermal effect, damaging the integrity of the cell membrane, interfering with the transporter mechanism, and causing microbial death, but its validity remains to be investigated [58,59]. Unlike the conventional thermal technique, the heat from RF is generated by electromagnetic waves acting directly on food rather than based on thermal conduction or convection. This results in less heat loss, a high heating efficiency, and a more uniform temperature distribution. As well, the wavelength of RF is 20–360 times longer than the commonly used MW, so its penetration depth is deeper and can be used to process food with large thicknesses [60,61]. RF has also been applied in the microbial control of a wide range of prepared dishes Table 4.

Table 4
Applications of RF to prepared dishes.

Prepared dishes	Power (kW)	Frequency (MHz)	Electrode gap (mm)	Time (min)	Microbial control effect	Quality change	Reference
Braised Beef	—	—	30	30	RF treatment reduced TPCs by 1.55 log CFU/g, and the shelf life of dishes was extended by 28 d at 37°C	No significant sensory difference ($P < 0.05$) is observed between the treatment and control groups	[40]
Kung Pao Chicken	6	27	20	10 20 30	Treatment for 20 min reduced TPC by about 1 log CFU/g	No significant sensory difference is observed in the evaluation between the treatment and control groups	[62]
Twice-cooked Pork	6	27	20	10 20 30	Treatment for 20 min reduced TPCs by 2 log CFU/g	Treatment for 20 min caused less damage to the quality of Twice-cooked Pork	[63]
Chinese Yam/Chicken Semi-liquid Paste	6	27	20	10 20 30 40	Treatments lasting 20 min or more could effectively reduce TPCs	Extending the treatment time to 40 min would seriously harm food quality	[64]
Boiled Crab Meatballs	6	27	—	10 20 30 40	Treatment for 30 min decreased TPCs by 2.25 log CFU/g and the product complies with the Chinese National Standard	Treatment for 30 min inhibited the production of a fishy odor	[66]
Spicy Pork Slices	6	27	160 170 180 190 200	—	Superheated water treatment at 124°C (plate gap: 190 mm) for 12 min reduced *G. stearothermophilus* by 5 log CFU/g	An electrode gap of 170 mm maintained a better sensory evaluation	[67]
Boiled Gansi Dish	6	27	120	8 12 16	Treatment for 12 min reduced *B. subtilis* by 3.62 log CFU/g	Treatment for 12 min caused less damage to the quality of the Boiled Gansi Dish	[69]
Stewed Pork with Carrots	6	27	20	10 20 30	Treatment for 20 min reduced TPCs by approximately 1.5 log CFU/g	Treatment for 20 min better preserved the texture and sensory properties of the dish and reduced lipid oxidation and carotenoid loss	[70]
Flavored Shredded Pork	6	27	20	10 20 30	Treatment for 20 min reduced TPCs by approximately 1.5 log CFU/g	Treatment for 20 min effectively preserved taste, volatile components, and water distribution	[72]
Pork	6	27	132	—	Treatment at 63°C and 71°C reduced *Salmonella* by 3.88 and 6.66 log CFU/g, respectively	No significant difference was observed among the cooking loss, total volatile basic nitrogen (TVB-N) content, and texture between RF, and water bath-treated samples	[73]

2.3.1. Applications of RF in prepared dishes

Using RF to deactivate microorganisms can not only ensure food safety, but also guarantee the edible quality of dishes, as it is a volumetric heating method with a lesser impact on food sensory. Pasteurization of Braised Beef using RF reduced TPC by 1.55 log CFU/g, with no significant sensory differences ($P < 0.05$) observed between the treated and control groups. Meanwhile, the shelf life of dishes at 37°C can be extended from 14 d to 42 d, and RF can reduce lipid oxidation compared to heat treatment in a normal water bath [40]. The TPC of Kung Pao Chicken treated with RF for 20 min met the Chinese National Standard (GB 2726–2016), whereas the chewiness, hardness, and flavor of Kung Pao Chicken were better than those treated with conventional thermal techniques [62]. Xu et al. [63] apply RF in the pasteurization of Twice-Cooked Pork, where treatment for 20 min reduced TPC by 2 log CFU/g, meeting the requirements of the Chinese National Standard (GB 29921–2013). In comparison with conventional thermal pasteurization, RF pasteurization caused less damage to the texture and flavor of the product, and the sensory score was closer to that of the control group.

To improve the microbial killing effect, RF is often used in conjunction with other techniques, one approach of which is to combine RF with bacteriostatic substances, such as zinc oxide, carbon dots, or chitosan [64–66]. Another strategy is to combine RF with hot water to heat prepared dishes to shorten the processing time and improve food quality [40,67]. Similar to MW, the variable shape and dielectric properties of prepared dishes are likely to cause non-uniform heating, which may produce microbial residues. In addition, to avoid secondary pollution, RF is usually used to process packaged prepared dishes. However, typical food packaging, such as polyethylene (PE) and polypropylene (PP), is unsuitable for RF processing because it is not heat-resistant. Wu et al. [68] investigate the impact of RF energy on the properties of PE and PP packaging materials, and although the mechanical properties of the packaging, including its tensile strength, elongation at break, and Young's modulus, did not change significantly with an extended RF heating time, the outer edges of the PE and PP packages melted after 3 min of treatment. Therefore, it is also necessary to consider the impact of RF on packaging materials and develop prepared dishes packages that are more suitable for RF treatment.

2.3.2. Factors affecting RF

The electrode gap can affect the RF heating rate, but generally, decreasing the electrode gap could enhance the electric field and increase the heating rate, but it is not linearly correlated [46], as an optimal electrode gap must always be determined to achieve the best heating and energy utilization efficiency. Wang et al. [67] use RF to treat Spicy Pork Slices, but the heating rate decreased sharply when the electrode gap increased from 190 to 200 mm, and the killing efficiency of *GeoBacillus stearothermophilus* was highest at a 190-mm electrode gap, though it took the shortest time to achieve a 5-log reduction. The temperature increases when extending the RF processing time, leading to a better microbial control effect. In addition, an excessive processing time also results in quality degradation. Zhao et al. [69] use RF to pasteurize Boiled Gansi Dish for 8, 12 and 16 min, resulting in reductions of *B. subtilis* by 2.13, 3.62, and 4.63 log CFU/g, respectively. The microbial control effect was optimal at 16 min, but the hardness of Gansi significantly decreased ($P < 0.05$) after 16 min of RF treatment. Meanwhile, the scores for appearance, flavor, and texture were also significantly decreased. Xu et al. [70] also reach a similar conclusion when exploring the effect of RF treatment on Stewed Pork with Carrots. Therefore, it is necessary to choose an appropriate RF treatment time to kill microorganisms, as well as to ensure the quality of dishes.

The composition of food is also a crucial factor affecting RF treatment. Similar to MW, the dielectric properties of food have a significant impact on RF treatment, influencing the absorption and attenuation of RF energy in food. As such, the dielectric constant and dielectric loss factor are commonly used to describe the dielectric property of food, where the former reflects the ability of materials to store electrical energy and the latter the ability to convert electrical energy into heat energy [71]. Components in prepared dishes are complex, and their dielectric properties differ, which can cause inhomogeneity in RF processing. Wang et al. [60] measure the dielectric properties of each component in meat lasagna during RF treatment and find that the relative loss factor of sauce was approximately twice that of beef meatballs, mozzarella cheese, and noodles. Under the same operating conditions, the temperatures of sauces rose much higher than those of other components, possibly leading to localized overheating. As well, like MW, the shape of food affects the distribution of RF energy, leading to an uneven temperature distribution. Consequently, prepared dishes with a uniform shape are more suitable for RF treatment.

The packaging of prepared dishes also affects RF treatment. For instance, Xu et al. [72] use infrared thermography to measure the temperature uniformity of Flavored Shredded Pork during RF pasteurization, where the temperature distribution in the cooking bag was relatively uniform but the temperature outside the cooking bag suddenly decreased. This is likely because the cooking bag had a good barrier effect, reducing heat loss and facilitating RF pasteurization. This was consistent with the findings of the Twice-cooked Pork Dish and Kung Pao Chicken [62,63]. Meanwhile, Wang et al. [67] use a cylindrical package when applying RF to Spicy Pork Slices. The product is stratified in the container, the top layer is oil, the middle layer soup, while the bottom layer Spicy Pork Slices, but the overall heating rate of the bottom layer was slower than top layer. The geometric center exhibited the slowest heating rate and served as a cold spot. Xu et al. [73] place Pork into a cylindrical polypropylene container and find that the geometric center of the sample had the highest heating rate, of 5.92 °C/min, while the heating rate at the bottom edge was only 3.92 °C/min. Thus, the packaging of prepared dishes significantly influences temperature distribution during RF treatment.

2.3.3. Challenges of applying RF to prepared dishes

RF has been commercially applied in post-baking of biscuits, but it is still in the laboratory stage with regard to microbial control [74]. Compared with the conventional thermal technique, RF equipment is complex and expensive, the cost of which is estimated to range between 2686 and 64,482 dollars per installed kW, without considering operating costs [75]. In addition, a few companies are struggling to develop RF equipment suitable for food pasteurization/sterilization, limiting the application of RF to prepared dishes [76]. In addition, RF is more suitable for processing food products with a regular shape, which also limits the application of RF to prepared dishes. Furthermore, dish components have a profound influence on RF processing, so it remains a challenge to develop appropriate RF procedures for a wide variety of prepared dishes with acceptable heating uniformity. Introducing a water bath to the treatment to improve the uniformity of RF treatment may be a development trend in the future. Similar to MW, common aluminum foil-laminated packages are unsuitable for RF processing, so it is necessary to produce prepared dish packages suitable for RF processing.

2.4. *High pressure processing*

HPP is a non-thermal pasteurization method that involves applying a pressure of 100–1000 MPa to food [77], used for prepared dishes via non-continuous processing. The packaged samples are positioned in a processing chamber and pressurized using a pressure transfer medium, the most commonly used of which is water [78]. HPP changes the distance between atoms, and the strength of non-covalent bonds is influenced by this distance. For example, the strength of ionic bonds is inversely proportional to the distance between charged particles. Therefore, HPP has a destructive effect on non-covalent bonds, including ionic bonding, hydrogen bonding, hydrophobic interactions, and van der Waals' forces. This impact further affects the function of biomolecules and disrupts the balance of the intracellular environment. In addition, HPP can also cause damage cell wall and membrane of microorganisms, leading to alterations in cell morphology and achieving pasteurization [79,80]. HPP does not disrupt covalent bonds. Therefore, ascorbic acid, anthocyanin, conjugated linoleic acid, and other nutrients that are mainly maintained by covalent bonds could be preserved during HPP treatment. Moreover, HPP is a non-thermal treatment and has a minimal influence on heat-sensitive components. This characteristic allows for better preservation of food's nutritional value [81]. In addition, according to Le Chatelier's principle, the isostatic principle, and the microscopic ordering principle, HPP treatment is a uniform instantaneous process unaffected by product shape and size [82], and it has made progress in the pasteurization of various prepared dishes since the FDA permitted its use for commercial production of foods in 2009 Table 5.

2.4.1. *Applications of HPP to prepared dishes*

Devatkal et al. [83] treat Chicken Nuggets with 300 MPa for 5 min, leading to a TPC decrease to less than 1 log CFU/g, with no significant impact on the color and texture of the chicken. In addition, it extended shelf life of Chicken Nuggets by 2 weeks at 4°C. Singha et al. [84] treated Hilsa Curry with HPP (500 MPa, 5 min), leading to a reduction in TPC by 0.78 ± 0.15 log CFU/g, and the product treated with HPP exhibited higher color and texture scores compared to conventional thermal-treated (75°C, 5 min) products. Yi et al. [85] compare the effects of HPP (550 MPa, 5 min) and thermal pasteurization (85°C, 30 min) on Wine-marinated Shrimp, both of which reduced TPC below the detectable limit and prolonged the shelf life of shrimp by about 76 d at 4°C. However, HPP treatment reduced lipid oxidation and more effectively preserved the appearance, springiness, and chewiness of Wine-marinated Shrimp compared to the thermal treatment [85].

For low-acid prepared dishes ($pH < 4.6$), HPP treatment can kill pathogenic and spoilage microorganisms, but it is difficult to inactivate spores, so low-temperature storage is usually required to prevent spore germination [86]. To improve the pasteurization effect, HPP is often combined with other techniques, which not only enhances the microbial inactivation effects, but also shortens the holding time and improves the production efficiency. HPP treatment induces physical compression, and the compression process converts mechanical energy into heat energy, consequently resulting in an increase in food temperature, which is generally at a rate of 3°C/100 MPa for water. However, the different components of prepared dishes have varied compressibility and specific heat, possibly causing an uneven temperature rise during HPP treatment [87,88]. To control the temperature during HPP treatment, a temperature monitoring system is usually integrated into HPP devices. As well, some devices incorporate a cooling system to mitigate the potential damage to food quality caused by temperature rises.

2.4.2. *Factors affecting HPP*

Numerous factors can influence HPP pasteurization, with pressure and holding time being the most critical among them, as generally, increasing these will enhance the pasteurization effect. Singha et al. [84] investigate the effect of HPP on the pasteurization of Hilsa Curry, but TPCs could only be reduced by 2.5 log CFU/g with 300 MPa treatment for 5 min at 60°C, while TPCs could be reduced by nearly 5 log CFU/g with an increase in pressure to 400 MPa. When the pressure increased to 500 MPa, TPCs decreased about two-fold, as much as 300 MPa, and when the treatment time was extended from 5 to 10 min at 400 MPa, TPC reduction could be increased by about 0.5 log CFU/g. Yet, pressure plays a more key role than time in pasteurization. Yuan et al. [89] observe a tailing phenomenon on the microbial inactivation curve during the HPP treatment of Boiled Bamboo Shoots, indicating that after reaching a certain time, extending the holding time is ineffective at improving inactivation intensity and may have a negative effect on food quality. The variance analysis shows that holding time has no significant impact on the pasteurization process when compared to pressure. Therefore, holding time could be appropriately shortened to improve production efficiency. To determine an appropriate pressure and treatment time, the Weibull kinetic model is commonly used for simulating and predicting microbial inactivation. Utilizing the Weibull model and taking pressure and time as independent variables, Yuan et al. [90] establish a microbial death prediction model for continuous HPP pasteurization processing that enables a more convenient prediction of the pasteurization effect on Boiled Bamboo Shoots and similar products under specified conditions. The pressure and holding time required to achieve the target pasteurization rate could be calculated, providing theoretical guidance for commercial applications.

2.4.3. *Challenges in applying HPP to prepared dishes*

HPP should not be used to treat dishes containing air bubbles, because the pressure can compress the bubbles and destroy the texture of the dishes [91]. Moreover, the rate of pressurization and depressurization can affect the inactivation of microorganisms,

Table 5
Applications of HPP to prepared dishes.

Prepared dish	Pressure (MPa)	Time (min)	Temperature (℃)	Microbial control effect	Quality change	Reference
Chicken Nuggets	300	5	27	After HPP pasteurization, TPC content was less than 1 log CFU/g, and the shelf life of the dish was extended by 2 w at 4℃	No significant changes in color and texture of the Chicken Nuggets	[83]
Hilsa Curry	300, 400, 500	5, 10, 15	40, 50, 60	Treatment at 500 MPa (50°C) for 5 min reduced TPCs by 0.78 log CFU/g	Treatment at 500 MPa (50°C) for 5 min well-maintained physicochemical properties	[84]
Wine-marinated Shrimp	550	5	25	HPP treatment reduced TPCs below 1 log CFU/g and prolonged the shelf life of shrimp by 76 d at 4°C	HPP-treated products had better sensory attributes than thermal-treated products	[85]
Boiled Bamboo Shoots	378	3	—	HPP combined with MW (20 W/g, 35 s) treatment reduced TPCs by 4.33 log CFU/g	No significant changes in overall acceptability	[89]
Boiled Bamboo Shoots	200, 300, 400, 500	1, 2, 3, 6, 9, 14, 20	—	Treatment at 400 MPa for 6 min or 500 MPa for 3 min reduced TPCs below 2 log CFU/g, and the pasteurization rate was above 99 %	HPP caused less damage to the quality of samples than thermal treatment	[90]

but existing conclusions present contradictory results [92]. Therefore, the changes in microorganisms at different rates of pressurization and depressurization must be investigated in depth to determine precise HPP treatment parameters. In addition, HPP may also change the pH of prepared dishes, potentially altering the microbiological control effect, but few studies have focused on instantaneous pH changes in foods under HPP treatment [93]. Solving the problem of measuring in situ pH under pressure is crucial to a comprehensive understanding of the effects of HPP on the composition of prepared dishes. Furthermore, the efficiency of HPP is constrained by expensive equipment and batch processing, rendering it less competitive in terms of production costs compared to the conventional thermal technique. Depending on its equipment capacity (35–525 L) and degree of automation, the cost of an HPP system ranges from 0.6 to 4 million dollars, accompanied by higher operating and maintenance costs [94,95]. It is estimated that the treatment cost of HPP is between 0.09 and 0.22 dollars per kilogram, which is about seven times as much as conventional thermal treatment [94,96]. In the future, the cost of equipment should be further reduced, and the efficiency of processing should be improved to increase the competitiveness of HPP.

2.5. Irradiation

Irradiation is a non-thermal microbial control technique that exposes samples to γ rays, X rays, or electron beams. Irradiation rays can also be generated by both radioactive and machine sources. Specifically, γ rays are generated by the radionuclides ^{60}Co or ^{137}Cs, while X rays and electron beams are generated by electron accelerators [46]. γ rays exhibit superior penetration capabilities, at a depth reaching 40 cm compared to approximately 20 cm for X rays and only 8 cm for electron beams. Consequently, γ rays find extensive use in industrial irradiation. However, due to public concerns regarding radionuclides, there was gradual development of X rays and electron beams generated by machine sources [28]. Irradiation controls microorganisms through both direct and indirect effects, the former of which signify that electrons or photons of rays collide with atoms in microbial molecules. This collision generates an energy transfer, leading to the cross-linking, breakage, and degradation of biological macromolecules, such as DNA, RNA, and proteins, consequently disrupting their normal functions [97,98]. Meanwhile, the indirect effect means that irradiation induces the ionization of water molecules, resulting in the production of free radicals. These reactive substances further disrupt the normal function of microorganisms [99]. Irradiation is a safe technology; as early as the last century, WHO/IAEA/FAO investigated the safety of irradiated food, finding that irradiation can effectively eliminate microorganisms and food irradiated with does up to 10 kGy is not harmful to human health [100]. Currently, more than fifty countries have approved the use of irradiation in food processing [101] Table 6.

2.5.1. Applications of irradiation to prepared dishes

Some prepared dishes are unsuitable for thermal treatment due to product characteristics; for example, Jeotgal is a traditional type of fermented seafood dish in Korea that does not require high-temperature cooking, so thermal processing is unsuitable for such dishes, but the temperature of Jeotgal does not increase during irradiation, preserving the original flavor of the product [102]. Park et al. [103] apply irradiation to treat Ganjang-gejang with an initial TPC value of 6.2 log CFU/g and fungi value of 4.1 log CFU/g, neither of which were detected after exposed to 9 kGy irradiation. Li et al. [104] treat Crayfishes with 3.32 kGy irradiation, which could reduce TPCs by 1.2 log CFU/g. Over 9 d of storage at 0℃, the TPC value remained below 3 log CFU/g, conforming to the Chinese National Standard (GB 29921–2013). Typically, irradiation induces lipid oxidation, whereas γ irradiation treatment (2–8 kGy) increased the peroxide value of Guizhou Spicy Chicken [105]. Huang et al. [106] also find that the thiobarbituric acid reactive substance (TBARS) value of Smoked Chicken Breast increased from 0.096 mg/kg to 0.240 mg/kg when the irradiation dose was increased from 0 to 6 kGy, which was consistent with the research conclusions of Park et al. [103]. Lipid oxidation caused by irradiation can be attributed to the generation of free radicals, which have strong oxidation activity and facilitate fat oxidation.

Both irradiation and HPP are non-thermal techniques, but they differ from each other, as the latter does not cause a significant increase in temperature and has advantages in processing cold dishes. HPP involves boosting and decompression, and the pasteurization of prepared dishes must also be processed in closed containers, limiting the ability to achieve continuous processing and reducing processing efficiency. Conversely, irradiation does not have these limitations, as some irradiation equipment include a conveyor belt to achieve continuous processing. To reduce the negative impact of irradiation on a product's sensory properties, besides choosing a suitable irradiation dose, combining it with new packaging is also an option. In addition, the damage to the flavor of prepared dishes caused by irradiation can be reduced by lowering the product temperature and adding ascorbic acid. There are also inhomogeneities in dose distribution during irradiation, and the actual absorbed dose of food can be monitored with a dosimeter to maintain it within an acceptable error range. With tools like MCNPX2.6, appropriate dose distribution can be obtained by adjusting the parameters of the rays and the distance between the energy source and sample [107].

2.5.2. Factors affecting irradiation

The type and dose of irradiation have a direct effect on the microbial control of prepared dishes. For instance, Song et al. [108] compare the lethal effects of γ rays and electron beams on three food-borne pathogens in Bajirak Jeotkal. Further, the D_{10} values of *Vibrio parahemolyticus*, *Listeria monocytogenes* and *Staphylococcus aureus* treated with γ rays were 0.29, 0.64, and 0.63 kGy, respectively, whereas the D_{10} values of electron beam for these bacteria were 0.36, 0.79, and 0.81 kGy, respectively. This suggests that a lower dose of γ rays was sufficient to achieve an equivalent decontamination effect compared to electron beams. Park et al. [31] also reach a similar conclusion: when the treatment dose was 5 or 10 kGy, Bulgogi treated with γ rays had fewer TPCs than those treated by electron beam during storage for 90 d. This indicates that γ rays were more effective in pasteurization due to their superior penetration ability compared to electron beams. In addition, the higher the irradiation dose, the better the bactericidal effect. No

Table 6
Applications of irradiation to prepared dishes.

Prepared dish	Irradiation dose (kGy)	Microbial control effect	Quality change	Reference
Bulgogi	5, 10, 15, 20	Irradiation dose of 15 kGy reduced TPCs by more than 2.15 log CFU/g and extended the shelf life of Bulgogi at 35°C by 60 d	Irradiation-treated Bulgogi had higher sensory scores than thermal-treated products	[31]
Ganjang-gejang	3, 6, 9, 12, 15	Irradiation dose of 9 kGy and above reduced TPCs to less than 2 log CFU/g	With an increase in irradiation dose, the sensory quality of the dish was gradually destroyed	[103]
Crayfishes	1.25, 3.32, 5.30, 7.24	Irradiation dose of 3.32 kGy reduced TPCs by 1.2 log CFU/g and extended the shelf life of Crayfishes to 9 d at 0°C	Irradiation dose of 3.32 kGy caused minimal damage to the edible quality of Crayfishes	[104]
Guizhou Spicy Chicken	2, 4, 6, 8	Irradiation dose of 4 kGy reduced TPCs by 1.03 log CFU/g and extended the shelf life of Guizhou Spicy Chicken to 60 d at 4°C	Irradiation dose of 4 kGy minimally affected the physicochemical properties of dishes during storage	[105]
Smoked Chicken Breast	2, 3, 4, 6	Irradiation dose higher than 3 kGy significantly ($P < 0.05$) reduced TPCs	Irradiation doses higher than 3 kGy severely damaged the overall quality of Smoked Chicken Breast	[106]
Bajirak Jeotkal	0.5, 1, 2, 5	Irradiation dose of 5 kGy effectively killed *Listeria monocytogenes*, *Staphylococcus aureus*, and *Vibrio parahaemolyticus*, reducing TPCs to less than 1 log CFU/g	Bajirak Jeotkal treated with irradiation essentially had no irradiated taste, and its acceptability scores were close to those of the control group	[108]
Potato	1, 3, 5, 7, 10, 15	TPCs were reduced by 3.25 log CFU/g after irradiation (7 kGy), and it was below the detection limit when stored at 36°C for 30 d	Irradiation doses above 7 kGy resulted in a serious loss of Vc	[109]
Pulav	5, 7.5, 10, 15, 25	Irradiation dose of 7.5 kGy and above reduced TPCs by more than 0.78 log CFU/g and extended the shelf life of Pulav by at least 1 y at 28°C	Irradiation dose of 25 kGy slightly decreased the acceptability of dishes	[110]
Stir Fry Chicken Dices with Hot Chili	10, 20, 30, 40	Irradiation dose of 10 kGy reduced TPCs by about 1.4 log CFU/g, and the TPCs of treated dishes were lower than 1 log CFU/g when stored at 25°C for 1 y	There was no significant ($P < 0.05$) change in the sensory qualities of dishes during 1 y of storage	[111]
Sauced Duck	2, 4, 6	Irradiation dose of 6 kGy reduced TPCs by about 4.75 log CFU/g and extended the shelf life of Sauced Duck at 4°C by 27 d	Irradiation at 4 kGy combined with modified atmosphere packaging (40 % CO_2 + 60 % N_2) reduced organoleptic and physicochemical damage to Sauced Duck from irradiation	[114]

TPCs were detected in the Potato treated with doses above 7 kGy during 30 d of storage. However, TPCs were detected on day 7 after treatment with doses below 5 kGy [109]. Marathe et al. [110] also find that increasing the irradiation dose enhances the microbial inactivation effect when irradiating Pulav. Irradiation doses should not be excessively high, as an overdose can result in deterioration of the quality of prepared dishes. For example, Chen et al. [111] observe that a high irradiation dose of 40 kGy results in considerable damage to product flavor, leading to a significant reduction in the overall acceptability of Stir Fry Chicken Dices with Hot Chili. Changes to a food's sensory characteristics caused by high-dose irradiation are related to lipid oxidation and the decomposition of amino acids or carbohydrates. The degradation of hydroperoxides during lipid oxidation can also generate low-molecular-weight alcohols, aldehydes, and acids, introducing unpleasant odors. As well, the decomposition of certain sulfur-containing amino acids produces volatile sulfides, which can also destroy flavor [112,113].

Packaging also affects irradiation treatment, as the presence of oxygen can facilitate lipid oxidation. To reduce lipid oxidation during irradiation, vacuum packaging is an effective measure. Li et al. [114] irradiate Sauced Duck and find that the introduction of modified atmosphere packaging not only enhances microbial safety, but also delays the increase in the TBARS rate during storage. At the end of storage, the TBARS value was about 0.4 lower than that in the group separately treated by irradiation. Simultaneously, the change in biogenic amines and TVB-N slowed, and the product obtained a higher sensory score. Compounds in food packaging materials may migrate into foods during processing, so it is critical to determine the effects of irradiation processes on common prepared dish packaging. Ma et al. [115] investigate the effect of irradiation on food packaging materials with different components and brands, such as PA/CPP, PET/Al/PA/CPP, and PA/PE, and the results show that irradiation did not increase the migration of primary aromatic amines (PAAs), but reduced the PAAs in simulated food, which is a safe microbial control method. However, if the package contains prepared dishes with different compositions, whether the effect of irradiation on PAA migration is consistent with the previous conclusions concerning the interaction of fats, proteins, organic acids, and other components must be further verified.

2.5.3. Challenges in applying irradiation to prepared dishes

Currently, irradiated agricultural products are growing at an annual rate of 20–25 %, and the total annual global irradiated agricultural products has reached 1.48 million tons [116]. However, irradiation has not been used for the commercial microbial control of prepared dishes, as one of the biggest problems with irradiation is the lack of consumer acceptance. Consumers always associate it with radioactive elements, though studies have confirmed the safety of irradiation, limits the application of irradiation to prepared dishes. Therefore, establishing uniform standards to address consumer concerns poses a significant challenge in its application to prepared dishes [117]. The irradiation dose applied to food is typically less than 10 kGy, and this may not ensure the desired microbial control effect [118]. Meanwhile, γ rays generated by radionuclides, such as ^{60}Co or ^{137}Cs, cannot be halted at any time, necessitating strict protective measures to prevent leakage and monitor inherent safety risks. Electron beams generated by mechanical sources are safer, but they exhibit limited penetration capacity. Moreover, when generating *X* rays, the energy tends to dissipate in the form of heat, with a conversion rate ranging only from 8 % to 17 % [119]. Further investigations are still needed to address these issues. In addition, the cost of irradiation should be considered, the cost of which is estimated to be 0.01–0.15 dollars/kg and decreases as the volume increases [94]. Concurrently, the processing cost is also related to the radioactive source. ^{60}Co is more cost-effective than electron beams when the annual processing capacity is less than 23 million kg [94]. However, the annual processing capacity is limited for small companies, and the construction of irradiation processing support facilities also requires a large investment. In the future, increasing the cooperation of companies and establishing large-scale irradiation facilities to provide the centralized treatment of prepared dishes will help solve this problem.

3. Conclusion and future perspective

With the accelerated pace of life, prepared dishes have a broad development prospect, but microbial control remains a crucial step in the production of prepared dishes, not only guaranteeing the safety of prepared dishes, but also extending shelf life and improving economic efficiency. The conventional thermal technique, MW, RF, HPP, and irradiation are the most common microbial control technologies for prepared dishes, and we summarize their applications to prepared dishes. To provide a clearer overview of the development potential for each technology, we have compared them, as shown in Table 7. Economic costs were not considered, because currently, several microbial control technologies other than the conventional thermal technique have not yet been commercialized. Due to the characteristics of the technologies, different technologies are suitable for diverse types of prepared dishes. For instance, the conventional thermal technique is universal and suitable for all types of dishes, while MW has poor penetration ability and can only be used to treat dishes with limited thickness. RF is suitable for dishes with large thickness and a regular shape, while HPP is unsuitable for dishes containing air bubbles and irradiation is usually used for dishes with a low initial microbial load. In addition, these technologies have different requirements for packaging, such that the conventional thermal technique requires heat-resistant packaging. Because of the shielding effect of aluminum against electromagnetic waves, prepared dishes packaged in aluminum-based materials cannot be treated with MW and RF, while HPP treatment requires pressure-resistant packaging with good barrier properties. Finally, irradiation treatment has no unique requirements for packaging. Among these five techniques, the conventional thermal technique induced the greatest damage to the quality of dishes, though it was difficult to make comparisons with the other techniques. Overall, there is a wide variety of prepared dishes, and no technology is perfect and versatile. As such, we must select the most suitable microbial control technique based on the characteristics of different prepared dishes. In the future, the combination and complementary advantages of various technologies will be the development trend.

Table 7
Comparison of microbial control techniques for prepared dishes.

Techniques	Types of prepared dishes	Types of packaging	Advantage	Disadvantage
Conventional thermal technique	All types	Heat-resistant packaging	Mature equipment technology; easy operation; winning the trust of businesspeople and consumers	Serious damage to food quality (nutritional, texture, sensory, etc.), resulting in a waste of water resources
Microwave	Dishes with limited thickness	Aluminum-free packaging	Dielectric heating; heat dishes rapidly and volumetrically; better quality maintained than with conventional heating methods	Limited penetration depth (3–8 cm at 2450 MHz); Complex composition and shapes of dishes; Dielectric properties would affect MW distribution, resulting in uneven heating
Radio frequency	Dishes with large thicknesses and a regular shape	Aluminum-free packaging	Dielectric heating; heat dishes rapidly and volumetrically with deep penetration; better quality maintained than with conventional heating methods	Complex compositions and shapes of dishes; dielectric properties affect RF energy distribution, resulting in uneven heating
High pressure processing	Bubble-free dishes	Pressure-resistant packaging with good barrier properties	Non-thermal treatment; well-maintains the quality of dishes	Batch or semi-continuous processing; it cannot kill spores and can only be used for pasteurization
Irradiation	Dishes with a low initial microbial load	No special requirements for packaging	Non-thermal treatment; well-maintains the quality of dishes	γ rays cannot be halted at any time and require strict protection against leakage; low consumer acceptance; the appropriate irradiation dose in prepared dishes is usually less than 10 kGy, and higher doses tend to oxidize fats and damage the quality of dishes

Many factors limit the application of these technologies; on the one hand, the equipment and techniques are immature and expensive, and on the other, the related regulations and standards are imperfect, so consumers and food companies also need time to accept the emerging technologies. Therefore, future efforts should be directed toward the following areas:

1. Establishing regulations and standards for applying various microbial control technologies to prepared dishes to improve industry standardization and win the trust of consumers.
2. Developing new equipment and combining various techniques to complement each other, thus enhancing microbial control efficacy.
3. Using software and models to optimize the microbial inactivation process and improve the scientificity of techniques and reduce the costs of research.
4. Ensure microbiological safety while maximizing the nutritional and sensory qualities of prepared dishes to satisfy consumer demand.
5. Researching microbiological control conditions, packing, storage temperature, and shelf life for different prepared dishes to establish a systematic research framework.

CRediT authorship contribution statement

Xiushan Wang: Writing – original draft, Methodology, Investigation, Conceptualization. **Pu Jing:** Writing – review & editing, Project administration. **Chen Chen:** Methodology, Investigation. **Jinhong Wu:** Writing – review & editing. **Huiyun Chen:** Writing – review & editing. **Shunshan Jiao:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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