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COMPREHENSIVE REVIEW

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Recent advances in radio frequency, pulsed light, and cold plasma technologies for food safety

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Abstract
It has been the heartbeat of researchers and food engineers to discover the appropriate and effective technology for microbial control to ensure the safety of food. This is because microorganisms such as bacteria, fungi, viruses, and protozoa can cause contamination in food products. Many studies have published reviews on the use of single novel technology such as radio frequency (RF), pulsed light (PL), and cold plasma (CP) to process food to ensure food safety. However, no review has provided a comprehensive, detailed overview of the RF, PL, and CP treatments for pasteurizing food products in one publication. This study aims to review and present the future directions of RF, PL, and CP applications in light of various aspects of these technologies. The review concluded that although no novel technique (thermal or nonthermal) could adequately meet all the requirements for food safety, traditional thermal processes can be extremely useful in reducing and eliminating microbe contamination. However, they cannot be applied to temperature-sensitive foods. Besides inactivating microbial spores, traditional thermal processes can denature proteins as well as organoleptic properties, such as taste, nutritional value, and sensory characteristics, illustrating the importance of these novel technologies as an alternative to heat-based techniques. As a result of this study, hurdle technology is recommended since it has an additive effect and achieves better germicidal results.

KEYWORDS
cold plasma, food preservation, food safety, food shelf-life, microorganism inactivation, pulsed light, radio frequency

1 | INTRODUCTION

One of the biggest manufacturing sectors in the European Union is the food sector, with over €1.098 billion in turnovers. The sector is said to be employing 4.24 million people, as reported by Saguy et al. (2018). It is necessary to state that the demand for the supply of more safe, nutritious food is directly proportional to the world population. This means that as the population of the world increases, more demand for the supply of safe food with extensive shelf-life is expected (Michelini et al., 2018; Richie et al., 2018), especially for low fat and no fat, processed food products. Furthermore, in the food industry, there is increasing demand for safe naturally preserved foods that have received minimal heat treatment and are free of chemical additives (Orsat & Raghavan, 2014). As a result, food products of high sensory quality and increased functional and nutritional value with combined traditional treatment are now expected by consumers

(Subramaniam & Wareing, 2016). Minimally processed foods are more prone to microbial contamination unless novel approaches are employed for their preservation. To ensure food safety, harvested foodstuffs and food products must be treated at high temperatures to eliminate potentially pathogenic microorganisms, but such treatment can alter the texture, flavor, color, and appearance of the food (Maktabi et al., 2011). Traditionally, heating methods involve generating heat outside the food product to be preserved by combustion of fuels or electric resistive heaters and then transferring that heat to the product by conduction and convection (Pereira & Vicente, 2010). Thus, the question of heat transfer efficiency arises based on this method. Techniques that employ heating, including pasteurization, sterilization, drying and evaporation, are common practices in the food industry to ensure microbiological safety (Pereira & Vicente, 2010). This is possible through a thermal process or technique, whereby food is exposed to heat for a long time, thereby giving rise to the production of low-grade food (Iqbal et al., 2019). Notably, the amount of time a food is exposed to heat influences its nutrient content, with more extended thermal processing resulting in a more significant nutrient loss due to overheating.

On the other hand, some foods are sensitive to heat, so applying traditional thermal preservation techniques is more challenging. The preservation of foods by thermal technique is said to result in the formation of chemical toxicants in food that can harm the human body (Oz, 2020; Oz et al., 2016). These toxicants depend on the type of thermal technique employed to process foods. For instance, the formation of heterocyclic aromatic amines, which causes mutagenic effects on the body, is due to microwave cooking and deep fat frying. Also, barbequing meat brings about the loss of meat juices, which contain saturated lipids that are stored in the form of adipose tissue. This reduces the saturated fatty acid and increases the polyunsaturated fatty acid present in the end product. According to Oz (2021), the polyunsaturated fatty acid formed enhances the end product, making it more susceptible to lipid oxidation and decreasing the quality of food products, which influences an off flavor with reduced mouth feel (Oz, 2021).

With all these advances and demand, there has been a search and debate and controversy regarding alternative technologies to traditional thermal treatment, which has been done both in academic through scientific publications and industrial level by food processing researchers. One of the key topics of discussion and controversy is the statement that pasteurization has been achieved under non-thermal conditions with low electric field strengths. Generally, traditional thermal processing technologies denature protein and the nutritious quality of foods and do not effectively preserve fruit and vegetables. Besides, using chemical reagents causes environmental problems, can cause allergic reactions or even transform into carcinogenic agents. Having established this fact, this study presents alternative methods to traditional thermal processing technologies, such as radio frequency heating (RF-H), pulsed light (PL), and cold plasma (CP). It has been proven that these novel technologies can inactivate microorganisms. Jadhav et al. (2021) reported that the aforementioned technologies came into existence a few decades. The technology has the potential to unmask food for treatment within a fraction of seconds, thereby reducing or eliminating microorganisms in food and increasing its shelf life. Unlike traditional thermal methods, these processing technologies do not negatively impact the food's organoleptic characteristics, including the sensory and textural attributes which are usually affected by high temperatures. Consequently, in the case of food preservation, the nonthermal technologies (PL and CP) are preferable over the thermal technologies (RF-H), because the former does not form undesirable products or by-products in or on the surface of the food because it cannot be exposed to higher temperatures like its counterpart (Thirumdas et al., 2020). It is fascinating to note that these novel technologies under study quickly reduce and inactivate microorganisms on foods and surfaces, making them fast, environmentally friendly and efficient. Hence, due to their simplicity in terms of application and versatility, they are incorporated into the current processing lines, potentially being employed in the food sector for safety purposes. It is important to note that the original structure of the food being treated does not change during its operation (Santos Aquilar, 2019). Furthermore, on the preference for non-thermal process over the thermal process, the non-thermal technologies under study (PL and CP) are carried out at an ambient temperature and sublethal temperatures, thereby disposing of the antagonistic impact experienced in thermal technologies.

As one of the most critical issues in food processing, microorganisms in food pose a considerable risk to food safety and induces spoilage. It is common that microbes will persist in food even after conventional preservation treatments have been applied, particularly on the surfaces of food processing equipment. Hence, the need to utilize these novel technologies to inactivate microorganisms in food, food processing facilities and contact surfaces. Through literature search and comprehensive studies, the review provides evidence to support the above statement.

This article reviews the current status and advancements of RF, PL, and CP in the food processing industries to improve the quality of food products and safety for consumers while extending shelf-life. It also examines the effects of these nonthermal technologies on different food components and the factors, which are responsible for delivering optimal results as well as the mechanisms of spore-formers and microbial spore's inactivation, with a particular focus on their limitations and their potential to alter food processing techniques in the industry in future. This is the first study to explore the comparison of RF, PL, and CP technologies, providing data that can be used to make informed decision for the treatment of food to ensure safety. According to the review findings, food scientists, technologists/industrialists, and researchers will be provided with a guide and recommendation on the best approach of implementing novel and emerging technologies objectively. In addition, the review will also benefit readers outside of the food industry since non-thermal treatment is currently gaining interest within academia and industry due to its numerous advantages over traditional thermal processing technologies. In conclusion, the review indicated that hurdle technology would offer synergistic and combinative effects as it would represent a significant difference in food safety compared to the traditional heat processes discussed earlier and the novel technologies undergoing evaluation.

1.1 | Bibliometric analysis of the study

The term "bibliometric" deals with the statistical analysis focusing on scientometrics, which illustrates the characteristics and data such as publication and research output. Through bibliometric analysis, it is possible to assess the scientific activities and impact of research and its sources (Obileke et al., 2020). Scientific research in RF, PL, and CP from 2010 to 2020 (10 years) was retrieved from the Web of Science (WoS) database. The following search criteria are used to retrieve publications between 2010 and 2020 from WoS database: ***"radio frequency" OR "radiofrequency" OR "pulsed light" OR "pulsed-light" OR "cold plasma" (Topic) and 2010–2020 (year published) and Articles or Review Articles (Document Type).***

In order to determine the most active journal in terms of output of publications on RF, PL, and CP, the contribution to publications on these topics over 2010–2020 was analyzed. It was observed that over 20,000 journals participated in published articles within the study areas, which included original articles and reviews from 2010 to 2020. For simplicity, out of the 20,000 journals, only five journals have published >1000 articles, as shown in Figure 1.

According to Figure 1, Proceedings of Spie published the most articles with 1559 over Physical Review D and IEEE Access, which had 1510 and 1455 publications, respectively. Other journals on the 1000 series are IEEE Transaction on wireless communication and AIP conference proceeding with 1061 and 1059 publications, respectively, whereas the others are below 1000 publications. This might be attributed to the journal impact factor and article processing time and the integrity of the publisher and open access charges. These influences the author's choice in publication (Obileke et al., 2020).

2 | RF-H TECHNOLOGY

The usual contamination of pests and microorganisms on the limited shelf life of food, low risk of pathogen contamination, and no growth potential are compared to those in high water activity or vegetal derived products. It is reported that low moisture food contributes extensively to food borne infections and outbreaks (Jiang et al., 2020). RF heating treatment is known as a dielectric heating technology for food pasteurization and disinfestation. The success of this technology can be attributed to its rapid and volumetric heating with a very large penetration depth. It is mostly applicable to low moisture food as a result of the contribution or role of dipole dispersion and ionic conductivity.

On the other hand, the technology as a thermal technique is recently gaining attention and interest in the food industry. Radiofrequency is a volumetric heating method that provides fast and deeper heat generation within the food matrices. Figure 2 shows a schematic diagram of a RH-H technology for food safety. For RF heating technology to occur, electromagnetic waves of 1–100 MHz are recommended (Jiao et al., 2018). This particular frequency has the tendency to penetrate inside the food and interact with the ions, atoms, and molecules to generate internal heat. According to Zhang et al. (2022), RF-H came about as an alternative to chemical fumigation and traditional methods because it is relatively easy to

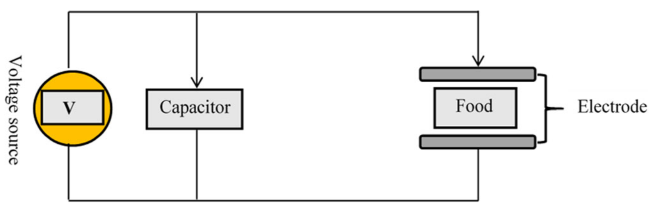

FIGURE 2 Schematic diagram of RF system (adapted and modified from Altemimi et al., 2019)

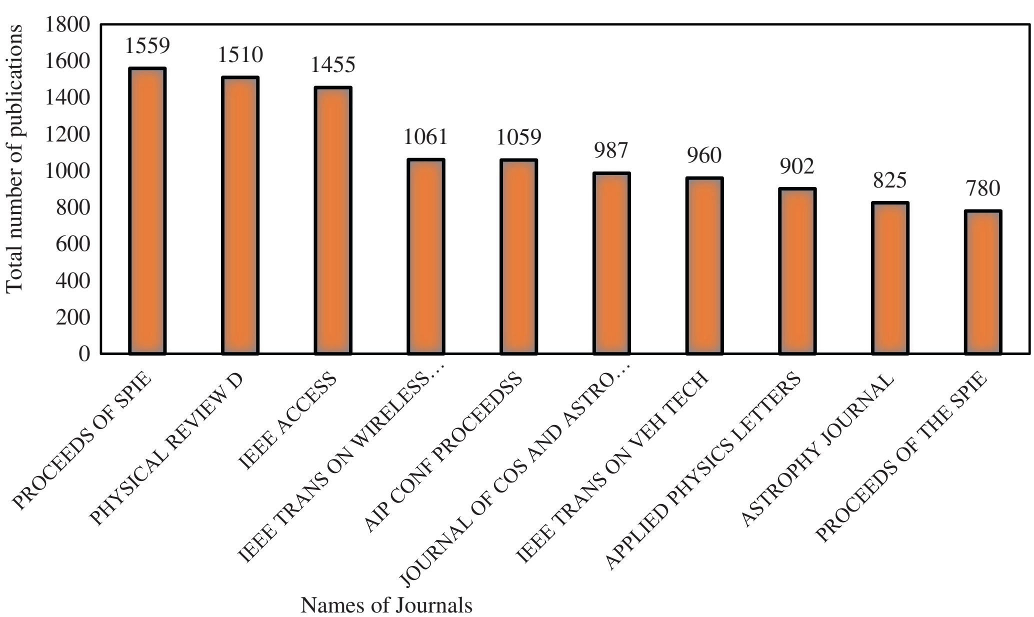

FIGURE 1 Lists of journals with the highest publications from 2010 to 2020 (the first 10)

operate without any chemical residues present. This development came about because of the recent pathogen occurrence, which has made the food industry seek an alternative way of pasteurizing food commodities. To compare RF and microwave, both are nonionizing forms of electromagnetic energy, however, RF has a longer wavelength, whereas microwave is of shorter wavelength (Mitchell 2016). Interestingly, RF aims to sterilize, pasteurize, and disinfect food and agricultural products such as fruits, dry nuts post-baking (Tanase et al., 2015). In addition, it has the capacity to kill microorganisms or pests because of the heat generated without damaging the product. This is attributed to the large difference in dielectric loss factor present between the target microorganism and the host food (Jiang et al., 2020). One major challenge of RF heating is the non-uniform heating which is caused due to the unavoidable uneven distribution of electromagnetic fields in the material (high moisture content like fresh foods) and the environment (Zhu et al., 2017). Therefore, to enhance the thermal uniformity, the use of RF is recommended to be used with combined surface heating such as hot air or water, assisting with sample movement of mixing (Hou et al., 2014). Furthermore, the use of computer simulation can be useful in predicting the electromagnetic field, thereby allowing for modifications to improve the uniformity of the RF-H. The best way of doing this, as suggested by Ferrari-John et al. (2016), involves adjusting the position, geometrical shape of the food sample as well its environment.

According to Jiao et al. (2018), RF is the lengthy exposure to high heat source temperature, which results in food quality degradation between the heat source and food material. However, RF heating creates a solution for the preservation process involving a treatment agent in contact with the food products because of its use of an electromagnetic energy of a longer wavelength than the microwave, which is of greater interest in the industry. RF processing is an example of an unconventional method for food treatment. Their electromagnetic waves are used to heat food products (13.56, 27.12, and 40.68 MHz), as seen in Table 1. However, the electromagnetic wave is electrical and magnetic energy moving together through space. Table 1 presents the design properties of RF in the food industry with their corresponding values/information.

Interestingly, an electromagnetic wave has to deal with the penetration of a certain dielectric material. With this in mind, from Table 1, it can be observed that RF have more penetration depth and longer wavelength than a microwave. This advantage ensures suitability for material heating with better uniformity.

TABLE 1 Properties of RF heating technology (Jiao et al., 2018; Ştefănoiu et al., 2016)

Design properties	RF
System construction	Simple design
Heating technique	Ionic charge migration
Operational frequencies	13.56, 27.12, and 40.68 MHz
Vacuum wavelengths	22.1, 11.1, and 7.4 m
Tap water penetration depth	1.58, 0.79, and 0.53 m

2.1 | Design of RF-H technology

In industries, a free-running oscillator (FRO) or open circuit and 50-Ω system are two ways RF can be designed (Mitcham et al., 2004). Table 2 shows the comparison of the two designs. It can be observed that the applicator is the common component present in the two designs of RF.

2.2 | Design description of FRO system RF

In Figure 3, the oscillator uses a thermionic tube that acts as a resonant circuit to produce RF at a specific operational frequency. This occurs after the line power from the AC main is transformed to a high voltage and converted into DC power by the rectifier. The RF energy transmits the product load placed between the electrodes to produce heat within the load through dielectric loss. Interestingly, about 98% of industrial-sized RF heaters are said to be developed on this type of design because of their simplicity, flexibility, and less expensive. However, the FRO design type of RF is the most common design when considering RF heaters. Furthermore, the FRO system is popularly employed in drying (cookies, crackers, textiles, paper, and glass fiber). This application is made possible because of its distinct moisture profiling characteristics present in FRO design RF. The function of the characteristics focuses more on wet areas than dry areas and then on dry areas and areas of moisture distribution in food during the drying process. Another application of the moisture profiling characteristic in food industries has to deal with protecting foods from being overheated during drying, reducing protecting foods from being overheated during drying, and reducing moisture content variation in the final product (Laudan, 2009).

TABLE 2 Differences between a FRO and 50 Ω RF system (Laudan, 2009)

FRO RF	50-Ω system RF
Consists of a high voltage transformer, a rectifier, an oscillator tube, a tuned circuit, an impedance coupling, a matching circuit and an applicator, as seen in Figure 1	Consists of a fixed frequency crystal driven oscillator, a solid-state amplifier, a dynamic automatic impedance matching network, and an applicator, as seen in Figure 2
Most commonly used and available in the market with established knowledge	New technology and few applications in the market
Easy to set up, operate, and maintain	Requires specialist for its operation, maintenance as well as setting up, especially in machining the generator to the load
Input power automatically machines the load, which has the advantage of selective heating	Constant power does not adjust power automatically with the variation of load moisture content
Low cost	High cost, using expensive electrode tube

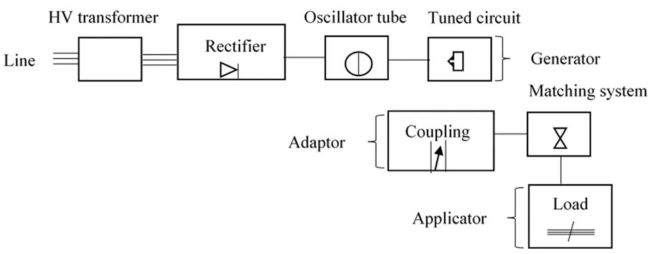

FIGURE 3 Detailed schematic diagram of a typical FRO design RF (Monzon et al., 2004)

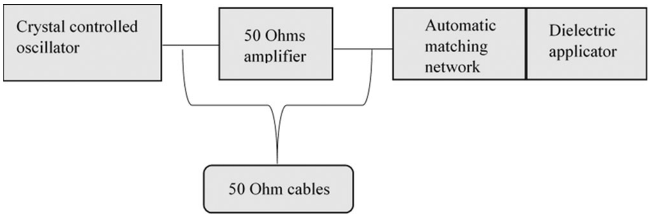

FIGURE 4 Schematic diagram of 50-Ω design RF (Mitcham et al., 2004)

2.3 | Design description of 50-Ω system RF

In Figure 4, the crystal-controlled oscillator, 50 Ω amplifier and automatic matching network are connected to the 50-Ω cables. The function of the crystal-controlled oscillator is to control the RF generator's frequency as it generates fixed output impedance. To achieve a maximum power transfer, the design is made. The impedance of the applicator with the load matched to 50 Ω, thereby allowing the power consumption and voltage on the electrode system to be displayed on the control panel. The 50-Ω system RF is characterized to have a more stable frequency output due to its matching system in the RF heaters. The application of this type of design system is suitable for treating food products with relatively stable moisture contents such as pasteurization and sterilization purposes. However, the 50-Ω is more expensive than the FRO system (see Table 2) because of its difficulty and complexity in setting up and maintaining.

2.4 | Factors affecting the performance of RF-H technology

Various factors are responsible for the successful application of RF heating for food products. Such factors include the following.

2.4.1 | Dielectric properties

This is expressed as a relative dielectric constant and relative dielectric loss factor. The relative dielectric constant is the amount of incident power absorbed or reflected, while on the other hand, the relative dielectric loss factor measures the amount of energy dissipated or transmitted with the food (Tewari & Juneja, 2008).

2.4.2 | Frequency

RF takes its frequency from the range of frequencies in the electromagnetic spectrum. The individual frequency is said to have distinct advantages for different categories of material and scope for the scale of food processing. As indicated in Table 2, RF band 13.56, 27.12, and 40.86 MHz are commonly used during the commercial-scale dehydration of textile, paper, and some food products (Dev, 2012). RF is relatively inert to frequencies of food constituents except for moisture and lipids.

2.4.3 | Property of food and temperature

The shape and size of food material under heating affect the temperature distribution due to the influence of the food sample shape on RF absorption. Ştefănoiu et al. (2016), stated that the size of the equipment for RF is directly affected by the shape of the products and depends on some thermal properties (thermal conductivity, density, and heat capacity) as a result of the heating characteristics of food. Ahmed and Ramaswamy (2004), stated that food's thermal conductivity contributes to dielectric heating to support this. This is because higher conductivity material dissipates heat than those of lower conductivity, especially as it concerns microwave heating. Different materials have different dielectric properties. The change in temperature often occurs during heating and affects the dielectric constant, dielectric loss factor, loss tangent, and heating behavior (Uyar et al., 2015).

2.5 | Advantages of RF technology

The advantages of RF technology are longer wavelength, absence of electrode contacting the food, simple construction design, and higher energy use efficiency, which improves the quality of the final product, applicable for industrial application mostly liquid and solids foods.

2.6 | Disadvantages of RF technology

The disadvantages of RF technology are higher equipment and operational cost, lower power density, slower heating rate, high efficiency, and output quality.

2.7 | Mechanism of microbial inactivation using RF-H technology

The successful implementation of this technology for food preservation and processing is due to its mechanisms of inactivation. Dielectric heating properties and electromagnetic waves are the mechanisms associated with RF heating technology. These are associated with thermal effects generated by frictional interaction between the polarized molecules and charged ions in food materials (Kou et al., 2018).

Therefore, dielectric properties are intrinsic properties of materials that describe the degree of a material's interaction with an alternating electric field, thereby quantifying its ability to reflect, store, and transmit electromagnetic energy (Jiao et al., 2018). The use of a jacketed sample holder with a circulating oil/water system enables the control of temperature during the dielectric measurement of RFs. In addition to that, Jiao et al. (2018) mentioned that placing the dielectric probe and sample holder in a heating or cooling chamber can control the temperature throughout the measurement. Factors such as frequency, temperature, food composition, and density are responsible for dielectric properties. For the electromagnetic wave of RF-H, Challis (2005) mentioned that this might polarize water and denature macromolecules such as protein and nucleic acid. During this process, the experienced changes of charge near the cell membrane are caused by the alternating electromagnetic field of the RF, which results in dysfunction of the cell membrane leading to cell death (Cleary et al., 1996).

2.8 | Applications of RF-H technology in food safety

Commercially, the application of RF can be found in the wood, textile, and paper industries as well as in the food industry. Therefore, most applications of RF can be explored in the food industry for the inactivation of microorganisms in food products, especially low water activities foods, including dried vegetables. Though microorganisms may not grow in low water activity foods, they have the tendency and potential to survive for a long time. Zhao et al. (2017) conducted a study on RF heating to inactivate microorganisms in broccoli powder. The broccoli powder of low water activity a_w of 0.586 was pasteurized using RF treatment. The experiment was carried out in a pilot-scale RF system of a polypropylene plastic pouch (17 × 12 × 5 cm) of power and frequency rates of 6 kW and 27.12 MHz, respectively. As a result of the RF treatment, there was a great reduction in the level of microbial inactivation by 4.2 log colony forming units (CFU/g) with an insignificant change of color for 5 min. The observation revealed that RF treatment is a promising technology with the potential to inactivate microorganisms, thereby contributing to good retention of food quality, mostly low moisture products. Generally, red pepper powder (*Capsicum annuum L*) is regarded as one of the commonly used spices because of its attractive color, taste, and pungency. However, the contamination of the powder is due to the microorganism, which occurs during handling, processing, transportation, and storage processes, including pathogens causing a food safety concern. As a result of this Jiao et al. (2019), investigated the effect of RF heating treatment on the inactivation of *Bacillus cereus* in red pepper at different water activity levels (0.56, 0.64, 0.70, and 0.74). As earlier seen in the previous study, in terms of design, a pilot-scale free-running RF (discussed earlier with diagram) heating system used in the study has the following properties: frequency (27.12 MHz), maximum power (12 kW), half mode (6 kW), two parallel plate electrodes (75 × 55 cm^2), the material used (polypropylene), diameter and height (8.9 and 4.3 cm^3), and temperature setting (20°C–80°C). During the RF treatment, it was observed that as the initial water activity level (a_w) increased, the RF heating rate increased at first and later decreased with the upmost point of 0.70. The optimum RF inactivation effect of 4 log reduction was obtained for a water activity level of 0.70 at 90°C within 110 s. The effect of inactivation *Bacillus subtilis* spores in soymilk using RF heating technology was studied by Uemura et al. (2010). It was reported that RF technology reduced *B. subtilis* spores in soybean milk by 4 logarithmic orders at a temperature of 115°C. Before then, the processed soymilk was placed at a frequency of 28 MHz. As part of the study's methodology, Teflon film was used to cover the electrode, which prevents scaling effectively. The result showed that tofu made with RF heated soymilk had higher breaking strength than tofu made with conventional soymilk. In this regard, the study concluded by mentioning that RF heating has the potential to enhance the safety of soybean and tofu quality. The current outbreak of *Salmonella enterica* and *Enterococcus faecium* on black peppercorn has called for an effective inactivation process due to the decontamination methods, which gives rise to quality deterioration. To solve this problem, Wei et al. (2018) recommended RF technology to provide a rapid heating rate and volumetric heating resulting in a shorter come up time. Second, the technology allows high temperature and short time combination to achieve the desired inactivation with minimal deterioration. In the study, the black peppercorns were inoculated with a five-strain cocktail of Salmonella or *E. faecium* to attain an initial population of 6.8 and 7.3 CFU/g. After that, they were adjusted to a moisture content of 12.7% (wet basis) and water activity of 0.60 at room temperature. The findings from the study revealed that the RF time of 2.5 min resulted in CFU/g reduction of 5.31 and 5.26, respectively. This data suggests that RF heating is a promising thermal inactivation treatment for *Salmonella* without significant-quality deterioration. On the other hand, *E. faecium* serves as a suitable surrogate for *Salmonella* to validate the efficiency of RF heating of black peppercorn. Similarly, the RF pasteurization process for the inactivation of *Samonella spp* and *E. faecium* on ground black pepper was carried out by Wei et al. (2019). The study was motivated as a result of the persistence of the microorganism, which causes several foodborne outbreaks and the safety of low water activity foods. Before the RF treatment, stability and homogeneity tests were conducted on both microorganisms during the moisture equilibrium to check their inoculation method. A reduction of more than 5.98 and 3.89 log CFU/g for the *Salmonella spp* and *E. faecium*, respectively, was reported due to the effect of RF heating for 130 s treatment time. Conversely, the use *E. faecium* indicates and acts as the suitability surrogate for *Salmonella spp* during RF heating of ground pepper. Interestingly, this was observed and reported in the previous study. From the findings, RF provides effective inactivation of *Salmonella* spp with insignificant <0.05 quality deterioration.

In fresh fruit processing, Lyu et al. (2018), reported that RF-H technology decreases the total aerobic bacterial (TAB) count by 4.81 log CFU/mL^{-1} as well as yeast and mold counts by 2.62 log CFU/mL^{-1} in kiwi puree. These treatment reports were said to be similar to traditional pasteurization (TP). However, the vitamin C, total phenolic compounds, and antioxidant capacity present in RF treated kiwi puree were significantly higher than those of TP treated ones. The good news was that the color and taste of the RF-H treated kiwi puree was retained better than the TP sample during the storage. During the processed fresh vegetables, the product is exposed to microorganisms, even foodborne pathogens, which are referred to as harmful and dangerous to consumers. Based on this, Liu et al. (2015), designed a RF-H system of power and frequency rate of 6 kW and 27.12 MHz, respectively, for the treatment of packaged Caixin (green leafy vegetable). The result showed that the RF-H could reduce the total colony number of vacuum packaged Caixin by 3–4 log CFU/g for 20 min. Hence, the sensory properties and color of the vegetable were almost the same as those of the control. For fresh foods, *Aspergillus parasiticus* is associated with corn, which is harmful to animals and humans. The application of the traditional method (convectional heating) for its treatment was costly and caused a negative effect on the food material. As a result of this, an alternative was made through the use of RF-H technology. Zheng et al. (2017), used a 27.12 MHz and 6 kW pilot scale RF-H system combined with hot air to pasteurize the *A. parasiticus* in corn at 70°C for 12 min. This was reduced to 5–6 log CFU/g of *A. parasiticus* in corn. It is also revealed that the parameter of the physiochemical properties of the RF-H corns met the requirement of quality standards in the corn industry.

To conclude this section, it will be interesting to look at the application of RF-H in fresh aquatic foods. Seafoods are rich in nutrition with delicious taste. They are generally common among consumers, and as a result, they are easily perishable during transportation and storage because of their high moisture and soluble protein content. To extend the shelf life of seafood, it is advisable that they are heat-processed without affecting their nutritional content and quality. In a study conducted by Xu et al. (2017), it was observed that 20 min RF sterilization of *Nostoc sphaeroids* achieved a reduction of bacterial population count of <10^3 CFU/g. The study also reported a lower effect on the parameter of color and flavor as a result of the RF-H sterilization of the sample with better performance than when compared with high-pressure sterilization treatment. Overall, RF-H is used to dry, bake, and thaw frozen meat and meat processing. Using the RH-F technology, Piyasena et al. (2003) summarize the successful applications of the technology. This is outlined in Table 3.

TABLE 3 Application of RF-H for food processing (Piyasena et al., 2003)

Type of application	Heating frequency (MHz)	Food present
Tempering	10–300	Meat
Pasteurization	60	Cured hams
	27	Sausage emulation
Thawing	14–17	Egg, fruits, and vegetable
	36–40	Fish
Postbaking drying	27.12	Cookies and cracker and snack food
Cooking and roasting	60	Cocoa bean

3 | PL TECHNOLOGY

RF has previously been discussed as thermal process technology and its advantages and disadvantages. Few technologies have been introduced regarding the unique properties of light, which are aimed at treating a variety of foods and food-related microflora (Koutchma et al., 2019). The efforts are made to explore these for purposes of preservation operations, as they have the potential to improve quality, nutrition, and functionality. But there are many advantages and disadvantages of PL technology, which lead to differing applications. Its specific emission spectra, inactivation mechanisms, and a multitude of benefits are marked characteristics of PL technology (Koutchma et al., 2019). Therefore, using this process, it is possible to overcome some of the limitations of thermal process technology as it gains popularity in the food industry. In a nutshell, PL technology, as a nonthermal technology, has the feature of a high-intensity light pulse with a short duration that sterilizes and decontaminates food surfaces and liquids with high transmission (Bhavya & Umesh, 2017). Guerrero et al. (2016) explained that PL produces heat but does not have an adverse effect on the food products, thus allowing microorganisms to be inactivated. The PL technology focuses primarily on treating transparent liquid foods, food surfaces, and food packaging materials (Koutchma et al., 2019; Oms-Oliu et al., 2010). Oms-Oliu et al. (2010) published a review covering the principles, mechanisms of microbial inactivation, and PL technology food preservation applications, including critical process factors that have to be optimized to improve efficiency. By combining PL technology with other traditional and emerging hurdle technologies used for a variety of foods, effectiveness can be significantly improved, which will pave the way for industrial-scale application in the future (Guerrero et al., 2016). Since PL processing method's effectiveness is limited by light-cheese interactions, the possibility of improving its effectiveness by combining it with the antimicrobial nisin and antifungal agent natamycin using *Pseudomonas fluorescens*, *Escherichia coli* ATCC 25922, and *Listeria innocua* as challenge microorganisms, have been explored and reported in the literature (Proulx et al., 2017). The results demonstrate that the combination of antimicrobials such as nisin and PL processing increased the inactivation of spores forming bacteria on cheese surface, but the order of treatments is critical. In 2003, PL, heat treatment at 40°C and 45°C for 3 or 15 min, and Ultraviolet-C (UV-C, $\lambda = 254$ nm) irradiation were used in different combinations for surface decontamination of strawberry fruits inoculated with conidia of *Botrytis cinerea* (Marquenie et al., 2003). The researchers found that the combination of PL and thermal treatment delay spoilage of fungal conidia, requiring lower temperatures than heat alone for inactivation. It is, therefore, possible to improve the effectiveness of the decontamination and spores' inactivation process by combining PL technology with other methods such as UV light, thermosonication (TS), pulsed electric fields, manothermosonication, MTS (Mahendran et al., 2019), antimicrobials peptides, and supercritical carbon dioxide (Hart et al., 2022). There is no doubt that the synergistic effects of combining PL processing with other antimicrobial treatments will provide better insight into potential applications of PL technology in the future.

PL gets its energy from the UV part of the spectrum. The U.S. Food and Drug Administration (FDA) approved the PL technology in 1996 to produce, process, and handle foods and decontamination of food contact surfaces (FDA, 1996; Rowan, 2019). It is defined as the use of intense light in the form of short pulses on a target interest in food or food contact surface to destroy microorganisms. For the past 15 years, PL has been a promising minimal process to enhance microbial safety or extend the treated food's shelf life (Schottroff et al., 2018). According to Schottroff et al. (2018), PL is classified as high-intensity pulsed UV light (HIPL), pulsed UV light (PUV), high-intensity broad-spectrum UV light (BSPL), intense light pulsed (ILP), and pulsed white light. According to Franco-Vega et al. (2021), the HIPL disinfects food by using a short duration, high intensity, and broad spectrum light, which can delay food spoilage through the destruction of pathogenic microorganisms. This process takes place through photothermal, photochemical, and photophysical mechanisms. Notably, they are primarily affected by the UV fraction of HIPL. Unlike UV disinfection, PL technology acts mainly on food surfaces and is currently applicable to transparent fluids.

In general, the PL is most effective when used to treat surfaces of food products and packaging materials. This purpose is due to the action or development of a thin surface layer that is sufficient to destroy or kill superficial vegetative cells (Ortega-Rivas, 2012). However, food products such as ready-to-eat, freshly cut fruit and vegetables, and decontaminated meat and fish are treated using PL technology. According to Cassar et al. (2020), in numerous food products, including chicken, fish, eggs (liquid and shelled), and powdered ingredients, microbial reduction can be achieved through PL. Hence, it has the potential and capability to improve the quality of food products, thereby killing microorganisms like *Listeria monocytogenes* within seconds (Pollock et al., 2017). The PL technology is regarded as a non-thermal process method because the inner layers are not affected by any rise in temperature. Comparing the PL technology with the traditional heat sterilization, both technologies tend to kill microorganisms because of the high temperature. However, Kim et al. (2019) reported that the PL technology has the advantage of energy-saving, high efficiency, and safety, and can effectively destroy the microorganism while maintaining the color, quality, and taste of the food. This advantage is very rare when traditional heat sterilization is being used. Besides, PL is also used to sterilize packaging material and equipment surfaces (Buchovec et al., 2010; Rajkovic et al., 2010). The sterilization effect of PL depends on the intensity of light (J/cm^2) and the number of pulses (Fang et al., 2020). However, the operation of the PL technology has to deal with the storing of energy in a high power capacitor for a long period and then released into a design xenon lamp device in a shorter time, usually nanoseconds to milliseconds. Thereafter, the high energy injected into the lamp then produces ILP, which usually last several 100 ms (Fang et al., 2020). As the sterilization effect of PL increases, the light intensity also increases. It is important to know that the destructive effect on microorganisms using PL lies in the rich content of broad-spectrum UV light, short time and high peak power (Fang et al., 2020). However, it is reported that the removal of wavelength range below 320 nm UV, indicates no lethal effect on microorganisms by PL technology. Therefore, the PL destroys nucleic acids while the UV light of wavelength 253.7 nm in PL destroys microbial DNA (Mandal et al., 2020).

3.1 | Design of PL technology

Pulsed-field light devices operate through the conversion of high-speed electronic pulses occurring at a short time and high peak energy pulses using engineering technology that is magnified several times. Hence, the system has three components. These include the power unit, pulse configuration device and lamp unit, as shown in Figure 5.

In Figure 5, the power source is brought about by the high voltage current, which is obtained from low voltage AC voltage. The high voltage capacitor is joined in parallel, concentrating on energy from the power source in the charge cycle and then releasing that during the discharge cycle; thereby, generating a high electrical current. The capacitor is also connected to the switch that performs the on/off cycle for a very short time, which converts low electrical power into pulsed, high electrical power. This description forms the pulse configuration device. The designed batteries of flash lamps contain exciting gases in the lamp unit because of the pulsed high electrical power from the pulsed configuration device discussed earlier. The high intensity from the PL is then delivered to the products by various lamp footprints and configurations (Mandal et al., 2020).

Moreover, as seen in Figure 5, the xenon emits a broad spectrum light flash in the range of about 200–1100 nm with ~25% UV light (Kramer et al., 2017). Currently, there has been an improvement in the design of PL. This has to deal with the kinetic system that moves particle around and the light source modality that combines HIPL with other technologies (Franco-Vega et al., 2021).

3.2 | Advantages of PL technology

The absence of mercury, unlike in the UV continuous system (Thirumdas et al., 2016, 2017), impact less risk from pathogens, provide improved and enhanced quality of the food product than thermal processing, low operational cost, provides flexibility, and absence of chemical and biochemical residues (Bulbul et al., 2019).

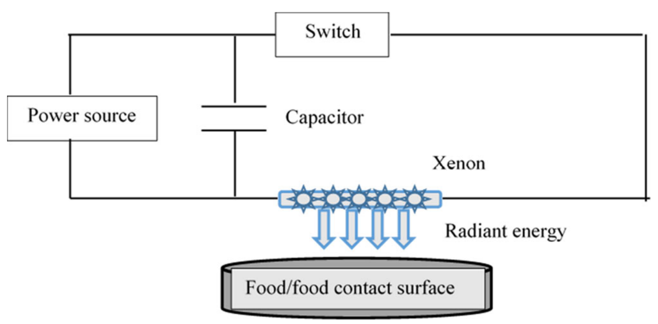

FIGURE 5 Schematic diagram of PL system (adopted from Mandal et al., 2020)

3.3 | Disadvantages of PL technology

The presence of opacity of food products leads to deterioration in organoleptic qualities, nonuniform surfaces, and the mechanism by which PL induces cell death is yet to be fully explained.

3.4 | Properties of PL technology

The properties of PL technology are cumulative treatment, not more than 12 J/cm^2, pulse width of not >2 ms, electromagnetic radiation of UV rays having a wavelength of 200–400 nm (Mandal et al., 2020), infrared rays, and visible light having a wavelength of 700–1100 nm and 400–700 nm, respectively (Mandal et al., 2020), frequency of 1–3 Hz (Thirumdas et al. 2016), and pulses employed in food industry emits 1–20 flashes per second on the surface with the energy level in the range of 0.01–50 J/cm^2 (Liu, 2019).

3.5 | Factors/parameters affecting the performance of PL technology

Various factors contribute to the performance of PL technology for food safety. However, selected factors are briefly discussed below:

3.5.1 | The number of light sources

This involves the presence of organic matter, particle size, and turbidity (liquid), which negatively impact the efficacy of the performance of the PL technology (Garvey et al., 2014). The photoreactivation and repair as well as length of exposure to daylight or darkness, have been reported to be the methods for microbial enumeration and PL treatment (Fitzhenry et al., 2018). The UVC induced DNA damage is responsible for the cell and molecular mechanistic factor governing the PL treatment (Ramos-Villarroel et al., 2011, 2012).

3.5.2 | Frequency of pulses

For the effective and efficient performance of PL technology, a frequency of 1–5 Hz is recommended. The scanning electron microscopy and transmission electron microscopy are employed for microbial enumeration and PL processing evaluation (Huang et al., 2018). The frequency of the pulses results in or is responsible for the possible overheating of the intracellular fluid (Xu & Wu, 2016).

3.5.3 | The spectral range of light flashes

For the efficacy of spectral light flashes, Wang et al. (2005) and Levy et al. (2012) reported 250 nm and 225–280 nm, respectively. The spectral range of light flashes is associated with environmental parameters such as temperature, osmotic stress, and illumination conditions (Kramer et al., 2017). This resulting loss of intracellular constituents, including protein as cell and mechanistic molecular factors governing PL processing technology (Garvey et al., 2016).

Having looked at the factors affecting the performance of PL technology, the nature of the food product or sample makes the technology different from others. PL processing is a light-based technology, therefore, the topography of the material tends to compromise the safety of the product. This results from the irregularities that protect microbial cells from light pulses. To this effect, particle size, food composition, exposure, turbidity, sample depth and distance, optical, and physicochemical properties are known as factors related to a food product that can affect the efficacy of PL technology (Arnold et al., 2020; Mandal et al., 2020). As an example, the PL processing method cannot be applied to foods high in protein and oil. This is attributed to the radiation from UV light absorbed by the proteins and oil, thereby interfering with killing and destroying pathogens (Arnold et al., 2020). Higher exposure time of liquid food results in higher inactivation, and the lower the distance, the better the treatment. Moreover, the turbidity of the liquid food affects the PL because of light scattering. In terms of opaqueness, opaque foods such as milk required opaque higher fluence (Krishnamurthy et al., 2007; Smith et al., 2002). For the food composition, Miller et al. (2012) revealed that PL processing efficiency decreases as the liquid food and total solid content increases. In another account, Mandal et al. (2020) mentioned that most food materials show a decrease in light intensity while penetrating their bulk, which appears in the form of heat, resulting in high temperature. Therefore, the process of PL is different for solid and liquid food. In solid food, PL is absorbing and gives rise to exponential and steeper decay of light intensity than in solid foods. The absorption of light is a function of the depth of the food product and its absorption coefficient. According to Heinrich et al. (2015), the lower the absorption coefficient and the higher absorption of the food product, the transmission coefficient increases the PL penetration. Also, the smooth product is a factor in the effectiveness of PL due to the microorganism totally exposed to light flashes. It is well known that solid food surfaces tend to be rough in most cases. In other words, the superficial area of the food product should also be taken into consideration. Therefore, complexity arises from the unevenness of the surface together with other factors such as oil and water contents and the shadow effect, which reduces the effective radiation dose required to achieve total decontamination (Mandal et al., 2020; Oms-Oliu et al., 2010).

3.6 | Mechanism of microbial inactivation using PL technology

The mechanism responsible for the inactivation of microorganisms under the PL technology includes the photochemical, photothermal, and photophysical effects. These mechanisms can occur independently or combined. However, Mandal et al. (2020) reported that the photochemical effect might be the main influencer that drives the destruction of microorganisms even though the photothermal and photophysical do have effects. But in general, PL effectively inactivates bacterial spores and decontaminates food and packaging material. Table 4 presents the different mechanisms of microbial inactivation by PL technology as reported in previous studies.

3.6.1 | Photochemical effect

The main factor of the germicidal effect of PL is the UV absorption by the DNA. The UV light is responsible for the antibacterial action due to the formation of pyrimidine dimer (Pollock et al., 2017). However, the light radiation of wavelength ≤253.7 nm gives rise to the energy to carry out dimerization of DNA. Regarding bacterial spores, Gómez-López et al. (2007) mentioned that treatment of spores using UV-C results in spore photoproducts such as 5-thyminyl-5, 6-dihydrothymine cyclo-butane pyrimidine dimers. Interestingly wavelength <295 nm can destroy viruses. In contrast, in a similar study, the wavelength of <400 nm was reported to destroy viruses because of the rupture of phage capsid (Gómez-López et al., 2012). Considering another facet of the photochemical effect known as photosensitization. Photosensitization is the accumulation of photoactive compounds targeted on microorganism cells followed by light flashes. As these photoactive compounds react in excess oxygen, cells are destroyed. The development of photosensitization is most likely to be new research relating to light-based technologies for food safety.

3.6.2 | Photothermal effect

The photothermal effect is possible for the inactivation of microorganisms once the final temperature reaches the pasteurization temperature. Although the application of high temperature by intense PL treatment also contributes to the inactivation of microorganisms in this case, it affects the food sensory quality (Mandal et al., 2020). Considering a few studies involving photothermal effect, Hiramoto (1984), reported that the absorption of light pulses into *Aspergillus niger* cells result in cell death because of the instantaneous heat mold. In Dunn et al. (1989) study, the potential use of light pulses to heat the food surfaces destroys inhabiting bacteria. This is attributed to the changes in the structure and physiology of the cell (photothermal stress). A similar study reported that the photo-thermal stress was responsible for the cell wall disruption in *B. subtilis* during the PL treatment (Nicorescu et al., 2013). Furthermore, there were structural changes in the PL treatment of *E. coli* because of the overheating, intercellular water vaporization, and subsequent membrane disruption (Xu & Wu, 2016). According to Mandal et al. (2020), the heat produced from light pulse technology is not much effective and efficient than photochemical effects toward the inactivation of microorganisms.

3.6.3 | Photophysical effect

Photophysical is regarded as one of the factor mechanisms for microbial inactivation in food safety. The damage to the cell wall structure, shrinkage of the plasma membrane, and leakages of cell organelles are because of the high energy pulses experienced during the photoelectric mechanism using the PL technique. This was a finding reported by Krishnamurthy et al. (2007), in a microorganism known as *Staphylococcus aureus*. In addition, the PL treatment under the photophysical effect contributed to the changes experienced in cell shape and cell membrane in *Saccharomyces cerevisiae*. It also resulted in the illusion of intracellular components and protein, as studied by Takeshita et al. (2003). Macias-Rodriguez et al. (2014) and Ramos-Villarroel et al. (2012) studies revealed the contributory effect of photophysical on microbial inactivation using PL technology. In their studies, the cytoplasmic and structural damages in central depression in cells were observed in *L. innocua* and *E. coil* during the post PL treatment of egg, respectively. One major effect of the photophysical is the structural damages experienced because of the high energy pulses.

3.7 | Applications of PL technology in food safety

In 2002, the Food and Drug Administration (FDA) recommended and approved the use of PL technology for food treatment, especially for the inactivation of microorganisms (bacteria, fungi, and viruses). Prior to this development, PL technology was an effective technique for sterilizing solid's and liquid, transparent surfaces using batch or continuous processing. Although the penetrating power of PL seems to be weak as the transparency of liquid food decreases. Hence, PL is characterized to have a higher penetrating power to water and weaker penetrating power to liquid food with higher turbidity (milk products). In an aqueous solution, the lower the penetration of light, the lower the sterilization effect of PL (Fang et al., 2020).

An investigation to determine the effect of PL technology on blueberry was examined by Cao et al. (2018) in relation to the inactivation of *Salmonella* and to extend the shelf life, quality and beneficial compounds. A PL system of 9 J/cm^2 was set up, and thereafter the sample was then stirred in water during the treatment. Afterwards, the blueberries were stored at room temperature for 3–7 days. Results showed that the PL treatment of blueberries effectively removed the *Salmonella* and extended the blueberries' shelf life. The authors reported no effect on the quality attributes and beneficial compounds. A bacterial reduction of 1.3 log CFU/g was observed during the decontamination of salmon using PL treatment by Pedrós-Garrido et al. (2018), after the optimization treatment condition (9 s at 3.5 cm and dose of 152.6 mJ/cm^2). An evaluation of the effect of PL on pork skin was studied by Koch et al. (2019). For effective performance, the distance of the lamp from the food sample was 8.3 cm with a fluence of 9.11 J/cm^2 for 30 s. It was reported that the PL treatment reduced the *S. typhimurium* and *Yersinia enterocolitica* present in pork skin by 2.97 and 4.19 log CFU/cm^2, respectively.

Inactivation of *S. aureus* and *E. coli* O157: H7 on fresh kashar cheese with PL technology was examined by Keklik et al. (2019). Usually, the cheese surface becomes contaminated with pathogens because of improper handling or contact with an unhygienic surface, which takes place during or after processing. To address this, the

TABLE 4 Mechanism of microbial inactivation under PL technology

Microorganism	Fold reduction	Mechanism	Method of analysis	References
L. monocytogenes and *E. coli O157:H7*	7 log reduction	DNA and cell damage with an accumulation of double-strand breaks, single-strand breaks, and cyclobutane pyrimidine dimer	Genomic DNA electrophoresis and transmission electron microscopy	Cheigh et al. (2012)
S. cerevisiae	6.4 and 5.8 log reduction	Cell damage, encompassing loss and coagulated inner content, and cell debris	Transmission electronic microscopy and flow cytometry	Ferrario and Guerrero (2017)
L. monocytogenes	5-log reduction	–	–	Pollock et al. (2017)
L. innocua and E. coli	4.00 and 2.90 Log for *E. coli*, and 2.98 and 0.93 Log for *L. innocua*	Induction of sublethal injury	Plate count with selective media	Pataro et al. (2011)
L. monocytogenes, *E. coli*, *Salmonella enteritidis*, *Pseudomonas aeruginosa*, *B. cereus, and S. aureus*	2–6 log reduction	–	–	Rowan et al. (1999)
E. coli	4.0, 4.5, and 5.33 log	Damage to membrane integrity	Scanning electron microscopy	Preetha et al. (2021)
B. subtilis, *B. atrophaeus*, *B. cereus*, *A. niger Geobacillus stearothermophilus*, and *spores*	3 and 5-log reduction	No visible spore damage	Scanning electron microscopy	Levy et al. (2012)
S. cerevisiae	3.9, and 6–7 log reductions	Rupture of cytoplasm membrane, and other cell structures	Flow cytometry and transmission electron microscopy	Ferrario et al. (2014)
E. coli and S. aureus	5.94 ± 0.22 and 5.91 ± 0.20 log CFU/ml	Cell membrane damage	Scanning electron microscopy	Bhavya and Hebbar (2019)
S. aureus	–	Cell wall damage, cytoplasmic membrane shrinkage, cellular content leakage, and mesosome disintegration	Transmission electron microscopy and spectroscopy evaluation	Krishnamurthy et al. (2010)
L. monocytogenes and S. enteric serovar Typhimurium	Listeria 7 log and Salmonella 6.7 log	Membrane damage	Scanning electron microscopy	Kairyte al. (2012)
L. monocytogenes	1.7–2.2 log reductions	Cell wall and cytoplasm shrinkage, and leakage of the cellular contents from the cytoplasm	Transmission electron microscopy	Cheigh et al. (2013)
Aspergillus carbonarius and Aspergillus flavus conidia	1.2–1.7 log	Alteration of structure elements of the caryopsis	Light microscopy	Zenklusen et al. (2018)
B. cinerea	–	Damage including plasmalemma detachment from cell wall, cytoplasm collapse, and vacuolization of cytoplasm, disruption of cell wall and plasmalemma with massive loss of cytoplasm and/or disruption of organelles	Flow cytometry and transmission electron microscopy	Bernal et al. (2019)
E. coli and Salmonella typhimurium	3–4-log	Cell membrane damage	Propidium iodide uptake analysis and transmission electron microscopy	Kim et al. (2022)

kashar cheese was subjected to PL at different times (5, 15, 30, 45, and 60 s) in 5, 8, and 13 cm PL system. It was revealed that the most favorable inactivation of *S. aureus* (1.62 log CFU/cm^2) and *E. coli* O157: H7 (3.02 log CFU/cm^2) occurred at 45 s in 13 cm PL system. The study confirms that PL has the potential for postprocessing decontamination of semihard cheese surfaces.

PL technology is also applicable to the inactivation of enzymes, which deals with the absorption of UV light by protein and amino acid, facilitating photochemical inactivation of proteins. For instance, an evaluation effect of PL on the activity of polygalacturonase (related enzymes to food firmness) was conducted by Pellicer et al. (2019), interestingly, the result indicated 90% activation reduction after applying 128 J/cm^2. The authors opined that disruption of disulfide bridges tends to be responsible for the unfolding of enzymes. In a similar study, *Chromobacterium viscosum* lipase, another enzyme in the food industry, was treated with an intense PL in Jeon et al. (2019) study. The study reported that as the activity of the enzyme decreases, the pulse fluence, and treatment time increase. This might be attributed to the fragmentation caused by the enzyme inactivation treatment, which causes loss of tertiary structure. In another study, a microbial count of 2 log CFU/g was obtained to show the impact of PL on the physical quality of fresh tomatoes. These findings revealed small losses in firmness and little modification in the enzymatic activity of pectinmethyl esterase and polygalacturonase.

Liu (2019) experimented on the PL inactivation of *Salmonella* on the surface of Almonds and whole black peppercorns. The study aimed to develop an effective PL processing method to inactivate Salmonella and the impact of the method on the product quality. Part of the methodology of the study is the inoculation of Almonds and black peppercorns with a cocktail of four nalidixic acid-resistant strains of *S. enterica*, being treated with PL. This was covered with a quartz plate during the PL processing for 2–30 min. The study reported surface decolorization when dry almonds were exposed to the PL at 0.26 J/cm^2 for 3 min.

On the other hand, the PL treatment achieved 4.78 log reduction in *Salmonella* at 0.25 J/cm^2 for 10 min on a small scale pilot study temperature over 100°C. According to Liu (2019), the result negatively affected the quality of almonds. As a result, temperature cycling was conducted, which achieved over 5 log reduction of *Salmonella* between 80°C and 90°C after 10 min PL treatment. The treatment this time around was favorable to the almond's color and weight parameter. However, 4.84 log reduction after 8 min PL treatment of 0.25 J/cm^2 was achieved for the black peppercorn. Hence, temperature plays a significant role in the inactivation of *Salmonella*. This parameter is necessary to ensure a better quality of the sample. In conclusion, the study recommends high temperature and short time PL treatment for antimicrobial processing.

An investigation to evaluate the effect of direct and in-package PL treatment on the inactivation of *E. coli* O157:H7 in Romaine lettuce was studied. In the study, Mukhopadhyay et al. (2021), subjected the surface inoculated Romaine lettuce pieces (2.5 × 2.5 cm) to PL treatment for a maximum of 1 min (63 J/cm^2). The PL system was made using polyethylene with thicknesses 0.00254, 0.00508, and 0.00762 cm having an ample UV transmission of 54%–83% ability, used for packaging. It was reported in the study that the treatment resulted in 2.68 ± 0.37 log CFU/g reduction of the *E. coli* O157:H7 at the optimal dose, however, the log reduction was decreased to 2.52 ± 0.19, 2.31 ± 0.34, and 2.18 ± 0.25 log CFU/g for Romaine lettuce in 0.00254, 0.00508, and 0.00762 cm thickness packaging enclosure respectively. In addition, the author mentioned that no significant difference ($p > .05$) in the microorganism was observed because of the PL treatment. Therefore, the initial aerobic bacteria and mold and yeast population were reduced significantly ($p < .05$) by >1 log due to the treatment. Hence, the findings demonstrate that PL technique may be used to improve and enhance microbial safety and reduce postprocessing contamination of Romaine lettuce.

In chicken-based food products, the reduction of *S. typhimurium*, *Campylobacter jejuni*, and *E. coli* inoculated on lean and skin surface chicken thigh was conducted using PL. Cassar et al. (2019) reported the performance of PL toward the microorganism reduction. After the PL treatment, the microbial reduction at 5 and 45 s revealed the following results: 1.22 and 2.02 log CFU/cm^2 (*E. coli*), 1.45–2.09 log CFU/cm^2 (*Campylobacter*), and 1.55 and 2.42 log CFU/cm^2 (*Salmonella*). In eggs, Ouyang et al. (2019), used PL to inactivate *S. Enteritidis* inoculated in liquid egg whites. The study reported a significant reduction of 1.98 log CFU/ml after 45.6 J/cm^2 PL treatment. Gawlik et al. (2019) reported <1.0 log reduction of *E. coli* on beef strip loins after exposure to a range of PL fluence.

Rajkovic et al. (2017) evaluated the effect of PL to inactivate *L. monocytogenes* and *E. coli* O157: H7 on the surface of stainless steel knives (application on food contact surface). Before the treatment, the knife understudy was dipped into a 5% solution of meat extract or used to slice pork meat and then inoculated. The findings revealed that microbial reduction of 5.99, 4.69, 4.12, and 3.58 log was reported for the respective knives applications after 3.0 J/cm^2 fluence of PL. It is interesting to note that residual bacteria can be protected from direct exposure to PL by using a knife to slice meat products. As a result of these applications, PL has proven to be an effective decontamination method for food products, contact surfaces, and packaging materials, enabling a greater reduction of microbial contamination. However, further experimental evaluation is needed.

In addition to its application for decontaminating surfaces, PL can also be used for preserving juices and beverages by inactivating *Alicyclobacillus acidoterrestris*, *Bacillus circulans*, *Clostridium perfringens*, *S. enteritidis*, *A. flavus*, *B. cereus*, etc., which are spoilage microorganisms of significant industrial relevance (Oms-Oliu et al., 2010). The possibility of a continuous flow PL system for bacterial inactivation of *E. coli* (Gram-negative) and *L. innocular* (Gram-positive) in fruit juices (apple and oranges) was carried out by Pataro et al. (2011). The ratio of water: to juice of 6.8:1 and 6.2:1 for apple and orange juices were reconstituted. Approximately 10^6 CFU/ml was obtained as the microbial load, when volume of 500 ml was inoculated with pure culture suspension of either *E. coli* or *L. inocular*. The PL emits high-intensity light of 100–1100 nm, which lasts for 360 μs at a constant frequency of 3 Hz. It was observed in the study that the higher the quantity of energy delivered to the juice stream, the greater the inactivation level.

The findings from the study revealed that *E. coli* has a greater susceptibility than *L. innocua* in both apples and oranges as regards PL treatment. Hence, the treatment at 4 J/cm^2, microbial reduction in apple and oranges juices were 4.00 and 2.90 Log-cycle for *E. coli* and 2.98 and 0.93 Log cycles for *L. innocua*, respectively. Apparently, both strains of bacteria were found to have sublethal injuries during the study, showing that membrane damage contributes to bacterial inactivation.

According to Dhar et al. (2022), fruit juices should undergo a 5-log cycle reduction to ensure a low level of resistant pathogens. As a result of this information, a relationship between the manufacturer and consumer can be determined. While the manufacturer focuses on achieving the microbial safety and stability of the juice, the consumer is more concerned with high-quality juice. Consequently, Vollmer et al. (2020) studied pineapple juice's microbial composition, enzyme activity, and phytochemical composition following PL treatment. In terms of 5-log cycle reduction, the results of this study agree with those reported by Dhar et al. (2022). Here, the 5-log cycle reduction from them resulted from the treatment parameter used (2.4 kV, either 94 or 187 pulses: 757/1479 J cm^{-2}). It is evident from the results obtained that PL treatment offers a plausible alternative to conventional thermal preservation techniques. As a result of the treatment, the microbial load was reduced, and the antioxidant capacity, the desired enzyme bromelain, and the color were preserved better than the thermal treatment.

In conclusion, Bhagat and Chakraborty (2022) investigated the effect of PL treatment on the pasteurization of pomegranate juice, focusing on microbial safety, enzyme inactivation, and phytochemical retention. But the pomegranate is an ancient fruit crop cultivated in the tropical and subtropical regions of the world and consumed as a functional food (Putnik et al., 2019). Therefore, with reference to their consideration, the findings revealed that PL treatment at 761.4 J/cm^2 (2.7 kV for 90 s) achieved 5D reduction in *E. coli*, inactivating spoilage enzymes incompletely at 2988 J/cm^2. Also, the thermal treatment of 95°C at 3 min resulted in an enzymatically stable juice, which retained more bioactive than equivalent thermally treated juice. The authors summarized by mentioning that sensory acceptance of PL treated juice obviously is better than thermally treated samples.

4 | CP TECHNOLOGY

When an electrical current is applied to a gas, several reactive species are produced (UV photons, charged particles, nitrogen, and oxygen). These reactive species are called CP. It is also referred to as the partial ionization of gaseous molecules (Misra et al., 2019; Varilla et al., 2020). Over time, the CP has been regarded as a novel nonthermal technology with great potential for food decontamination and has recently attracted much interest for the application of food processing. The technology operates at a temperature of 25°C–65°C (Niemira, 2012). When gas is ionized, free radicals such as ions and electrons are produced. However, the composition of the ionized gas is a result of the composition of the reactive plasma species (Alves Filho et al., 2019). For instance, examples of gases used for plasma production include argon, helium, oxygen, nitrogen, and air (Misra & Roopesh, 2019). Plasma is said to found its way into many fields such as: chemical engineering, textile, electronics, pharmaceutical, and the food sector (presently as a case study). Therefore, in the food industries, CP is employed to reduce or inactivate microorganism load in foods and their surfaces, thereby improving food constituents' physical and chemical properties. Also, its application can be extended to the sterilization of food processing, inactivation of food spoilage and treatment of food packaging materials and wastewater (Chizoba et al., 2017). It is interesting to observe that CPs are commonly generated near ambient temperature, but microbial inactivation is dependent upon high temperatures. As a consequence, the temperature of the plasma used is considered ambient. Thus, there is no risk of thermally modifying heat-sensitive foods (Thirumdas et al., 2020). In recent publications, Nwabor et al. (2022) have described the most promising CP application designs, the mechanisms by which spore-formers and microbial spores can be inactivated, and how plasma treatment can disrupt biofilms. Notably, both PL and CP technologies can be applied in sterilizing or reducing the microbial population of packaging material surfaces or food contact materials in processing plants.

Figure 6 shows a schematic diagram of CP technology for food safety. As illustrated in Figure 6, CP technology usually consists of high voltage (preferable 200 W at a frequency of 50 Hz), filtered air, an electrode, and plasma. However, Corona T-Jet CP enables an indirect Corona treatment of low heat transfer into the surface of the food. This is generated inside the head between two electrodes (Figure 6) and thereby conveyed to the surface by an air stream. The purpose of the filtered air is to enable plasma generation, usually measured bar (pressure) at a constant flow rate in liter per minute (L/min). Usually, the process parameter considered for CP is a fixed distance of 35 mm, whereas the treatment width is ∼18 mm. Also, the recommended chemical characterization of the emission is in the range of 220–450 nm wavelength, which is carried out by an optic fiber probe placed about 20 mm from the discharge and connected to a spectrometer (Kilonzo-Nthenge et al., 2018).

Besides the food decontamination, another application of the CP involves the inactivation of enzymes, removal of toxin and pesticide residue, and the packaging of food. As in the case of PL technology

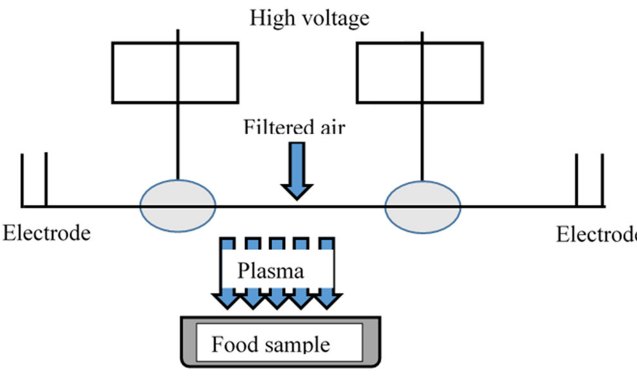

FIGURE 6 Schematic diagram of CP (Kilonzo-Nthenge et al., 2018)

discussed earlier, the CP's counterpart is effective against foodborne pathogenic microorganisms such as *L. monocytogenes* and *S. typhimurium*. In addition, the CP can destroy or kill microorganisms present in foods; Tulane virus in romaine lettuce, *C. jejuni* and *Salmonella* spp in meats, fruits, and vegetables (Varilla et al., 2020). The activity of CP improves the physiological properties of lipid, protein, and carbohydrates at a temperature range of 25°C–65°C in food, which is usually applicable in various food processing. For the purpose of improving the cooking and textural properties of food grains, gaseous CP performs best (Jadhav et al., 2021; Thirumdas et al., 2017). However, CP inactivates microorganisms found on the surface of the food product, thereby achieving desirable results (Bulbul et al., 2019; Cui et al., 2020). The use of CP cannot be overemphasized, as it is employed for surface sensitization of packaged fruit and food products such as vegetables and meat, which has shown promising results. Its application or advantage for the effective reduction of microorganisms is not an exception, as it prolongs the product's shelf life and reduces spoilage. During the food treatment by CP, it is interesting to know that the nutritional, functional, and sensory properties are affected by the action of CP on food products (Starek et al., 2019).

4.1 | Design of CP technology

CP operates under ambient pressure with the aid of oxygen, nitrogen, and a combination of noble gases (argon and neon). The use of CP for food sterilization can be divided be classified into three design configurations. Each of the designs has different characteristics as regards antimicrobial efficiency. This depends on the relationship between the target surface and the generated plasma. The three different designs are CP remote treatment, CP direct treatment, and CP proximity with one of the electrodes.

4.1.1 | Remote CP

In the remote treatment of CP, the targeted food product is not directly placed in the chamber where the plasma is produced, as shown in Figure 7. In terms of design, the remote treatment is preferred because of its design simplicity, the flexibility of the size and the physical shape of the target product. However, the design set-up is made so that the reactive species generated in the generation chamber can react with other plasma species, which results in lower secondary energy and lower potential microbial inactivation. Figure 7 shows the CP remote generator.

(N.B: *Though old reference, no recent source on this design type*)

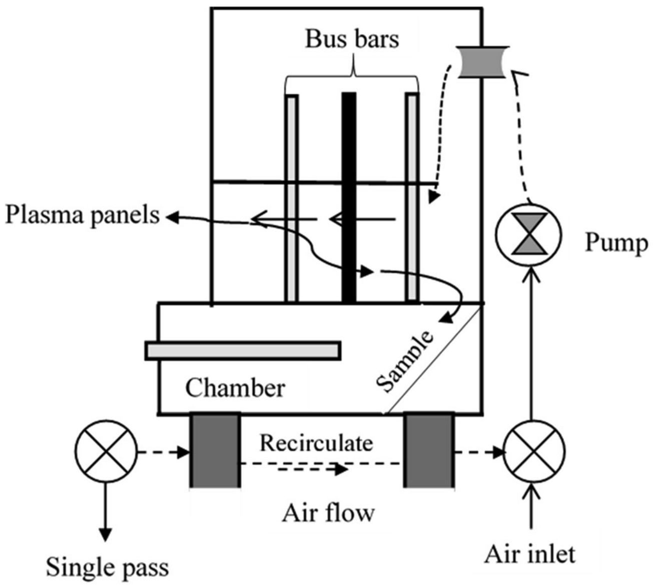

FIGURE 7 Remote CP generator (adapted from Ben Gadri et al., 2017)

4.1.2 | Direct CP

Here, the generated plasma is directly in contact with the target product. Therefore, the system design for the direct CP can be of plasma needle or microwave plasma tube. Interestingly, this type of design gives higher efficiency due to its direct proximity to the target compared to the CP remote treatment stated earlier. Table 5 presents different designs associated with direct CP.

(N.B: *Though old reference, no recent source on this design type*)

(N.B: *Though old reference, no recent source on this design type*)

4.1.3 | Close contact of the product with the electrode

The third design of the CP has to deal with the food product to be treated coming in close contact with one of the electrodes, as displayed in Figure 10. The design is made to expose the food target to the reactive plasma species and of relatively high molecular species, concentration, reactive charged particles, negatively charged electrons, and UV radiation (Sharma et al., 2000). However, the choice of selection of plasma parameter is important as regards to size and shape of the food to be treated. Therefore, this type of design, known as dielectric barrier discharge, is best suited for smaller products such as seeds, berries, and nuts, as well as chicken breast (Varilla et al., 2020).

(N.B: *Though old reference, no recent source on this design type*)

4.2 | Factors affecting the performance of CP technology

The factors influencing the performance and efficacy of CP technology for food safety can be categorized into microbial, plasma, and food factors. These factors are briefly discussed as follows.

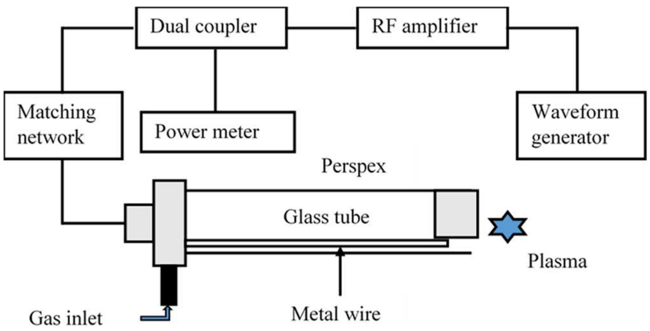

FIGURE 8 Flow diagram of plasma needle (adapted from Sladek & Stoffel, 2005)

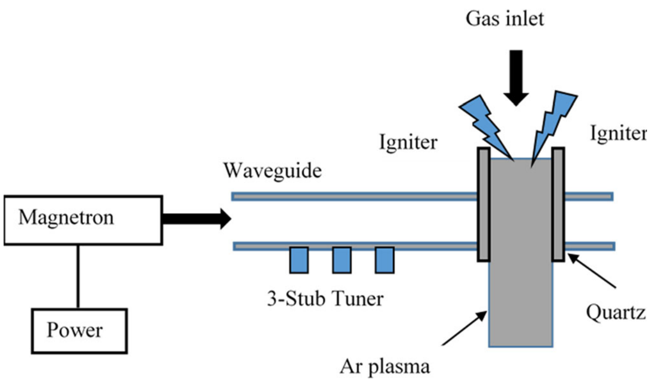

FIGURE 9 Microwave CP tube (adapted from Mehdizadeh, 2015)

TABLE 5 Plasma needle and microwave plasma tube comparison

Plasma needle (Figure 8)	Microwave plasma tube (Figure 9)
This is fed with helium (0.3 L/min)	This is fed with argon (100 L/min)
Requires RF of 0.2–0.5 Kv, 13.46 MHz	Requires microwave system of 1 Kw and 2.45 GHz
It has a total power consumption of ~20 mW–3 W, depending on the parameter of the treatment	It has a UV intensity which varies from 65 to 94 W/cm^2

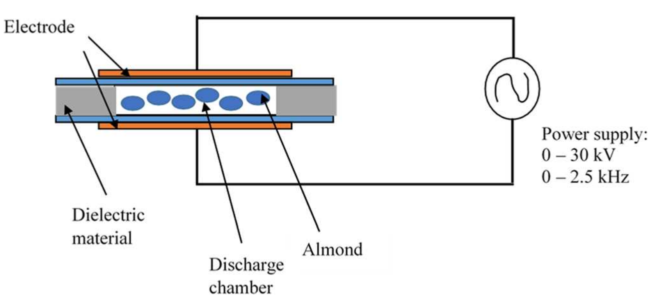

FIGURE 10 Dielectric barrier discharge (adapted from Deng et al., 2005)

4.3 | Microbial factor

The rate of microbial inactivation is directly proportional to certain parameters such as power, frequency, and voltage. This means that an increase in any of the parameters results in an increase in the rate of microbial reduction. Under the microbial factor, the following parameters are considered: cell wall and concentration, physiological state, endospores, and biofilms (Bourke et al., 2017).

4.3.1 | Plasma factor

Plasma is formed by the excitation of various gases such as oxygen and nitrogen; hence, the type of gas employed for plasma formation is important to the effectiveness of plasma mediated microbial inactivation. Having established that, interestingly, the presence of oxygen gas in the formation of plasma increases the microbial inactivation (Kim et al., 2014). This might be attributed to the production of ozone, a strong oxidizing agent used in water treatment as a disinfectant. The plasma factor focuses on the process (e.g., treatment time, sample positioning, relative humidity, and post-treatment storage time) and the system, such as gas type, gas flow rate, frequency, and voltage/power (Bourke et al., 2017).

4.3.2 | Food factor

This generally affects the food products' shelf life, nature type, moisture content, and microbial composition. To determine the efficiency and effectiveness of antimicrobial treatment using CP, the nature of the food constituents, such as fat, protein and carbohydrate content, need to be considered. Similarly, the inactivation of microorganisms through CP can be influenced by the water content of the food product. This is because of the high OH^- radicals produced during treatment, especially in the liquid water phase, which enhances and increases the inactivation of microbial cells (Shen et al., 2015). However, various condition contributes to this factor and are classified as solid and liquid. The solid deals with the composition, quantity structure/nature, and surface topology of the product, whereas the liquid, involves the nutrient content, composition, quantity (volume), and internalization (Bourke et al., 2017).

4.4 | Advantages of CP technology

The advantages of CP technology are low heat capacity, cost-effectiveness provides OH radical generations, eco-friendly and simple, economical and easy to use at room temperature and atmospheric pressure, capability to remove various toxic components found in wastewater (Li et al., 2020; Zeghioud et al., 2020), less power input for operation, does not damage the key food nutrient, suitable for treating raw and fresh food products, does not affect the sensory and nutritional properties of the food products, and equipment cost is low when low-cost noble gases are used for processing. CP is environmental safe provided that the reactive species are withdrawn from the power supply (Coutinho et al., 2018; Hertwig et al., 2018).

4.5 | Disadvantages of CP technology

The disadvantages of CP technology are the presence of lipid oxidation in fish, degradation of the oligosaccharides in juices, not suitable for all types of foods, volume and size of the food treatment are restricted, treatment of bulky and irregularly shaped food is a difficulty, several POS species have limited penetration into food products (Coutinho et al., 2018; Mandal et al., 2018).

4.6 | Properties of CP

CP can be generated at 1 atmospheric pressure with an electron temperature of 1 and 10 eV (Dave et al., 2019; Misra & Roopesh, 2019) and RF voltage of 40 KHz.

4.7 | Mechanism of microbial inactivation using CP technology

It is proven that CP technology can inactivate bacteria, spores, and microorganism contaminating foods and non-food surfaces. CP, however, is more effective by forming reactive species that are lethal to microorganisms that range from bacteria to fungi. Therefore, the mechanism of microbial inactivation via CP technology provides higher efficacy due to the direct nearness to the target. Although the technology is used to a higher degree of UV radiation exposure because of the nearness of the target, as earlier indicated, there is a tendency of conductor's heat in the products with respect to high moisture content and water activity (Niemira & Gutsol, 2011). Gururani et al. (2021) account that the inactivation of bacteria and fungi via CP involves the generation of reactive oxygen species (ROS), which is the major mechanism for inactivation. Other mechanisms include reactive nitrogen species, UV radiation, energetic ions, and charged particles (Han et al., 2016). To support this, the Sharma et al. (2018) study revealed that inactivation through CP resulted from genetic material, proteins, and cell envelops of pathogenic microbes, known as the target point. During the CP inactivation of microorganisms, malondialdehyde is generated, which disrupts genetic material that leads to the death of the cell.

In Thirumdas et al. (2015), DNA destruction resulting in cell components and membrane damage is because of the hydroxyl radical. In a similar development, the radical species exert antimicrobial effects through the process of induction of oxidative stress. This leads to the loss of cellular function and lysis of cells (Figure 11). The oxidative stress is responsible for the enhancement of cells damaged by membrane proration, lipid peroxidation and enzyme inactivation. The

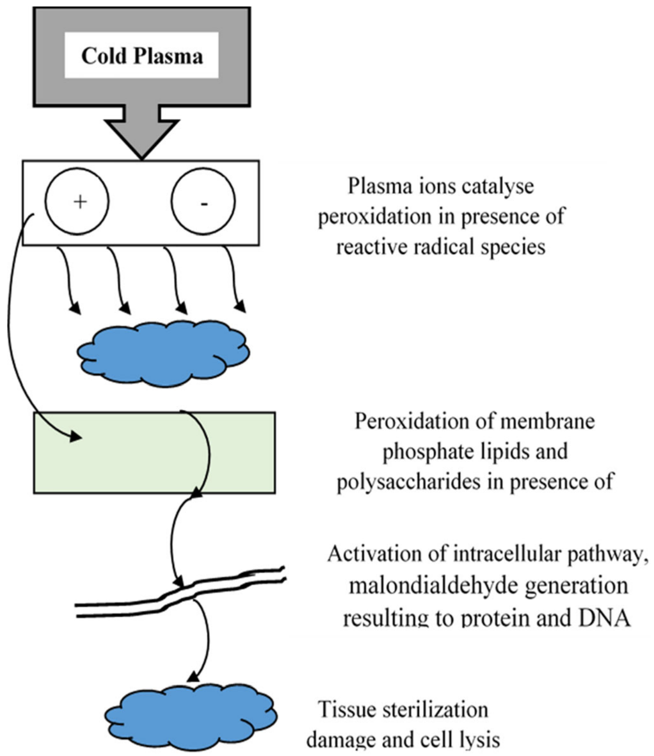

FIGURE 11 Schematic diagram of the mechanism of microorganism inactivation via CP technology (extracted from Dobrynin et al., 2009)

contribution of CP acts on multiple bacterial and fungal cell sites, resulting in structural and functional alteration and cell death (Misra et al., 2019). Another contribution of plasma species on the inactivation of microorganisms was reported by Pai et al. (2018), whereby NO and ions were minimal to the cellular effects while the presence of the ROS gave rise to rapid bacterial inactivation and induced eukaryotic and prokaryotic oxidative stress. As shown in Figure 11, the mechanism of the inactivation process is schematically illustrated by using CP technique.

4.8 | Application of CP technology in food safety

An exposure of *E. coli*, *S. typhimurium*, and *L. monocytogenes* inoculated beef tenderloin to 10 min of a plasma jet was carried out using nitrogen and oxygen gas mix. The author Jayasena et al. (2015) mentioned that 2.57, 2.58, and 1.90 log CFU/g microbial reduction was reported, respectively. During the study, it was interesting to note and observe that the 10 min CP treatment had no effect on the surface color but significantly increased lipid oxidation. In a similar study, Wan et al. (2017) revealed that 5.53 log CFU/g reduction of *S. enterica* serovar Enteritidis inoculated on the surface of shell eggs after 15 min exposure to CP modified atmospheric gases. In another study, Oh et al. (2017) examined the effect of CP treatment on *S. typhimurium* on the characteristics of radish sprouts. The CP was characterized as having nitrogen gas of power and pressure of 900 W and 667 Pa for 1–20 min. An optimum microbial reduction of 1.8 log CFU/g count of *S. typhimurium* occurred at 10 min. It was reported that the appearance and taste were not affected as a result of the treatment. The study showed no *S. typhimurium* growth as the radish sprout were stored in an enclosed plastic barrier package. Hence, this did not affect the radish sprout's water quality, color, antioxidant activity, and ascorbic acid. This confirms that CP has the potential to inactivate *S. typhimurium* on radish sprouts without affecting the sensory attributes. To assess the shelf life and effect of *E. coli* and *L. innocua* on Cherry tomatoes, Ziuzina et al. (2016) conducted the study using CP technique. Microbial reduction of 3–5 log CFU/g was observed on *E. coli* and *L. innocua*. In addition, no substantial variations were reported in terms of color, firmness, pH, and total soluble solids. The study stated that bacteria type, cell concentration, and mode of treatment are possible factors that might affect the efficiency of decontamination as well as to achieve an optimum microbial reduction in CP technology.

As mentioned previously, CP can be used to decontaminate or inactivate microorganisms. Researchers Lee et al. (2016), investigated and reported a case study of evidence. The study focus on the antimicrobial efficiency of *E. coli O157: H7*, *B. cereus*, *Bacillus subtillis* on brown rice. Although the author mentioned that CP treatment improved the microbial decontamination of brown rice, Pasquali et al. (2016) stated that Gram Positive *B. cereus* and *B. subtillis* took a longer time to inactivate when compare with Gram-negative *E. coli* O15: H7. From the study, it was obvious that CP treatment has a greatly significant effect on the water adsorption and activity of α-amylase and decreases the brown rice's pH and hardness. This study was conducted to demonstrate the effectiveness of CP technology in maintaining microbial safety and improving the textural quality of food.

In fruit processing, the use of effective CP technology helps to decrease the total aerobic count and total anthocyanin in fresh blueberries. Lacombe et al. (2015) confirmed this in a study conducted on the effect of bacterial inhibition on blueberries' quality attributes. The study reported that CP significantly lowered the number of microflora on blueberries stored at 4°C for 7 days and reduced the compression firmness after 60 s and anthocyanin after 90 s. In a similar study, CP was used to assess the agrochemicals on blueberries focusing on the nutritional and physical quality attributes. CP of 80 kV, during 5 min treatment was reported to reduce pesticide potency by 80% (boscalid) and 75% (imidacloprid). From the study, the ozone and hydroxyl radicals were said to be responsible for pesticide degradation. However, there was no effect of the treatment on the physicochemical properties (color and firmness). It is evident from the study that CP retains attractive nutraceutical properties and also is a promising technique for agrochemical reduction and microbial deactivation on fresh fruit. In another development in fruit processing, CP technique was used to inactivate *Salmonella* and *E. coli*, on the golden delicious apples. This was necessary to minimize or stop the contamination of fruit with human pathogens, especially in fresh fruit industries, which has become a reoccurring concern. First, two strain mixtures at 8 log CFU/ml of the bacteria were inoculated on the surface of apples, dried, and exposed to CP for treatment at a treatment of 35 mm. Kilonzo-Nthenge et al. (2018) reported that the bacteria were inactivated with the optimum reduction of 5.3 log CFU/cm^2 (180 s) and 5.5 log CFU/cm^2 (240 s) for *Salmonella* and *E. coli*, respectively. The findings add to existing knowledge that CP is a potential postharvest technology to reduce pathogens, especially in apples.

A study was conducted by Dirks et al. (2012) on skinless deboned chicken breast and skinless chicken thighs with skin in order to decontaminate their exteriors. The methodology employed in the study has to deal with the injection of antibiotic-resistant strains of *S. enterica* and *C. jejuni* on the understudy food, treated at an ambient temperature and pressure. After 3 min of the CP treatment, maximum reduction of *S. enterica* and *C. jejuni* was reported. Specifically, 1.8–1.3 log CFU on the chicken thigh and around 2.5 log CFU on the chicken breast were observed. On the other hand, there was a decrease in the composition of microflora on the chicken breast and thigh after 30 s treatment.

The efficacy of CP on the pathogen inhibition, sensory attributes and physicochemical of raw pork loins was published by Kim et al. (2013). As usual, the antibiotic-resistant strains of *E. coli* O157 and *L. monocytogenes* were injected and spread on the sample of the pork loins. In the study, the CP gases used were He and He + O_2 for the duration of 5 and 10 min. A reduction of 0.55 and 0.59 log CFU/g at 10 min was reported for *E. coli* and *L. monocytogenes*, respectively. The use of CP treatment did not affect the color of the food sample, rather there was a significant decrease in the pH. The study showed CP as a potential technique for the inactivation of the foodborne pathogen responsible for the decontamination of pork loins.

Having discussed the RF, PL, and CP technique for food safety, it will be interesting to briefly look at a comparison of these techniques. Though they might have similar things in common, their differences are of utmost importance. The comparison is presented in Table 6.

5 | APPLICATIONS OF HURDLES TECHNOLOGY FOR FOOD SAFETY

So far, the review has looked at some technologies (RF-H, PL, and CP) for food safety, focusing on their general overview, design, advantages and disadvantages, factors affecting their performance, and mechanism of their inactivation and applications. Having established that these individual technologies discussed earlier help in the decontamination and inactivation of microorganisms, its limitation has resulted in the invention and adoption of hurdle technology. Therefore, the emergence of hurdle technology provides a combination of technologies with each other or with traditional hurdles to achieve a higher inactivation level. This approach helps in eliminating microbial contaminants by providing a hostile environment, which disrupts the homeostasis of microorganisms in food permanently or temporarily and improves the synergistic effect against food spoilage microorganisms. It has been widely employed in different food such as fruit and vegetables, meat and meat products, fish and sea foods, and low moisture food (Table 7). The hurdle technology serves as an alternative to solve limitations in individual food processing techniques (Aaliya

TABLE 6 Summary of comparison of RF, PL, and CP

RF	PL	CP
Thermal process	Nonthermal process	Nonthermal process
Heat is generated in the center of the food (Maloney and Harrison, 2016). Applicable in rapid defrosting of frozen fish, meat, and processed foodstuffs sterilizing solid or viscous packaged food (Huang et al., 2016). Sanitizing dry food products such as dried fruit, legumes, and cereals (Huang et al., 2016)	Used for decontamination of surfaces in the food industry and packaging. Inactivate bacteria, viruses, and fungi faster than continuous UV treatment; Pasteurization process of fruit juices. Treatment of surfaces of food products and packaging materials (Huang et al., 2016)	Powerful disinfection tool for decontamination in the packaging of food productsUsed to dry disinfection of solid and liquid food (Lee et al. 2015)Fast technology does not leave toxic residues or exhaust gas Influences the nutritional content, color, texture, and quality of food (Dong et al., 2020; Korachi et al., 2015; Mason et al. 2015)

et al., 2021). In a nutshell, hurdle technology is the deliberate and intelligent use of a combination of existing and novel preservative techniques to establish a series of preservative factors that any microorganism present should not be able to overcome (Oh et al., 2019). According to Franco-Vega et al. (2021), the key objective of hurdle technology is to reduce the intensity of any one treatment in order to preserve the quality of food. Based on the literature review, it was found that pulsed light technology (HIPL) is a common novel technology used together with other technologies for effective treatment. Meanwhile, Franco-Vega et al. (2021) reported that there are currently combinations of methods for HIPL treatment in progress and that equipment for this treatment is being developed. This prompts the refinement that confers better treatment over a wider range of applications. To briefly discuss a few, Ferrario and Gurrero (2017) combined ultrasound (US) and PL on the structural and physiological changes of *S. cerevisiae* KE 162 in apple juice. The properties of the US are 600 W, 20 kHz, and 92.2 μm wave amplitude, at times 10–30 min at 20 or 44°C ± 1°C. On the other hand, the PL is characterized as 3 pulses/s, 71.6 J/cm^2, temperature ranges: 2–20°C ± 1°C and 44°C–56°C ± 1°C. The findings showed that US + PL treatment at the highest heat up resulted in 6.4 and 5.8 log cycles of yeast reduction present in the commercial and fresh apple juice, respectively. This effect occurred after single 30 min US and all combined US + PL treatment, 91.6%–99% of the treated cells showed compromised membrane. In a similar study by the same author Ferrario and Gurrero (2016), the effect of a continuous flow-through PL system with US was conducted on commercial and fresh-pressed apple juice. The study focus on the performance of the hurdle technology on the *S. Enteritidis* MA44, *S. cerevisiae* KE 162 and indigenous flora in the apple juice, laying emphasis on the microbial survivability, color, sensory, and shelf life. For the commercial and fresh-pressed apple juice, a 1.8–4.2 log reduction was reported for a single treatment whereas US + PL showed a 3.7–6.3 log reduction of inoculated microorganisms. In terms of the parameter and factors considered in the study, the freshly pressed apple juice was accepted by consumers because of its sensory shelf life of 25% reduction with 95% confidence observed.

Various food products have been preserved through hurdle technology (Qiu et al., 2019), thereby reducing/eliminating undesirable microbes without any detrimental sensory and nutritional attributes, as shown in Table 7.

Having seen the promising results of hurdle technology for selected food products in Table 7, the authors sought it necessary to briefly summarize these food products in respect to the microorganisms present and technology used for treatment, as presented in Table 8.

6 | CONCLUSION AND AREAS FOR FUTURE STUDIES

The review has successfully demonstrated RF, CP, and PL are unique, promising heating technologies for agriculture and food products microbial decontamination to ensure safety, inhibit spoilage, and extend shelf-life. With the tendency to replace traditional heating for food processing and preservation. Moreover, these novel technologies, which are still understudied, appear to be alternative methods for microbial and spores' inactivation of food products. Though these individual technologies have their own limitation and challenges, the employment of hurdle technology (combination of the thermal and nonthermal process) discussed proved to offer solutions relating to the drawback of the individual microbial decontamination process. It was clear from the study that the novel technology process provides different mechanisms for bacterial decontamination. The mechanism of microbial inactivation has been recognized as one of the major methods of evaluating the impact of novel technology in food processing and preservation. Hence, monitoring this process is an area of interest and concern. Therefore, requires further studies, especially regarding the validation of microbial inactivation mechanism by single or hurdle approach. While a variety of publications attempted to provide a sure mechanism for bacterial decontamination by novel technologies, our detailed review mechanism, accompanied by recent references of the literature, provided a more comprehensive overview. To conclude, from the literature, nonthermal processes (CP and PL) have proved critical to the food industry. It was obvious hurdle technology has a synergetic or addictive effect compared to a single technology. Previous studies revealed that the use of the hurdle process in food preservation exhibits antagonistic effects. Hence, further studies are recommended to assess and estimate the uncertainty when combining preservation interventions. After a thorough review of the literature, we recommend close collaboration between

TABLE 7 Recent application of hurdle technology in selected food products

Food types	Hurdle technology used	Targeted microorganism	Reported observations	References
Fruits and vegetables				
Apple	High intensity US + Slightly acid electrolyzed water + calcium oxide	*L. monocytogenes* and *E. coli* O157: H7	The treatment reduced >5 log CFU	Tango et al. (2017)
Fresh cut pepper	US + mild heating + Slightly acid electrolyzed water	*L. monoctogenes* and *S. typhimurium*	Reduced pathogens by ~3 log CFU/g	Luo and Oh (2016)
Iceberg lettuce shreds	PL + High intensity US + Chlorine wash	*Salmonella* spp	Resulted in <2 log reduction of the pathogen	Huang and Chen (2018)
Cherry tomato	High intensity ultra sound + Aqueous ozone	Mesophilic bacteria	Synergistic effect of >3 log CFU/g microbial reduction after 10 min of treatment	Mustapha et al. (2020)
Salted Chinese Cabbage	Plasma activated water + Sodium hypochlorite + Mild heat	*S. aureus* and *L. monocytogenes*	Reduction of 3.7 and 4.3 log CFU/g for *S. aureus* and *L. monocytogenes* respectively	Choi et al. (2019)
Meat and meat products				
Chicken breast	High intensity US + slightly acid electrolyzed water	LAB, mesophilic bacteria and psychotropic bacteria	0.81, 0.98, and 0.76 log CFU/g reduction of LAB, mesophilic bacteria and psychotropic bacteria, respectively	Cichoski et al. (2019)
Raw beef	Gamma irradiation + nonthermal plasma	*E. coli*	The treatment decreases the pathogen by 0.9 and 1.82 log CFU/cm^2 after 2 and 5 min, respectively	Stratakos and Grant (2018)
Raw chicken fillet	Ozone + lyophilization	Lactic acid bacteria and total aerobic mesophilic bacteria	A reduction of 4.77 log CFU/g of Lactic acid bacteria and a reduction of 6.8 log CFU/g of total aerobic mesophilic bacteria	Cantalejo et al. (2016)
Fish and fish products				
Smoked salmon	Ultraviolet + nonthermal process	*L. innocua*, *L. monocytogene*, *E. coli* O157:H7, *S. aureus*	The sequestration treatment in the reduction of 0.5–1. 3 log CFU unit of microbial population by an additive lethal effect	Colejo et al. (2018)
Raw salmon fillets	Ultraviolet + US + Acid electrolyzed water	*L. monocytogene* and total viable count	The technology reported a reduction of 0.75 and 0.64 log CFU/g of *L. monocytogenes* and TVC respectively	Mikš-Krajnik et al. (2017)
Low moisture foods				
Dried grape seed powder	Infrared heating + conventional heating	TAB	High microbial reduction rate of Table 3 23 ± 0.14 log CFU/g	Fu et al. (2019)
Chili flakes	Infrared + ultraviolet + ozone	*E. coli* MG 1655	Microbial reduction by 0.80 log CFU/g was observed by the synergistic lethal effect of the treatment	Watson et al. (2020)
Black peppercorns	Nonthermal process + ultraviolet	*Bacillus tequilensis* spores and mesophilic aerobic bacteria	Simultaneous treatment showed a reduction of 1.7 log spores/g and 3.4 CFU/g of mesophilic aerobic bacteria in peppercorns	Bang et al. (2020)
Raw pistachios	Infrared drying + temperature + hot air drying	*E. faecium*	Sequential infrared and hot air drying leading to reduction 6.1 log CFU/g in kernel and 5.41 log CFU/g in shell of pistachios	Venkitasamy et al. (2017)

TABLE 8 Microorganism and technology for treatment in various food products

Food products	Most technology used	Pathogen present
Fruits and vegetables	High pressure processing, High intensity US, UV, PL, nonthermal plasma	*Salmonella spp*, *Listeria spp*, *E. coli*, etc.
Meat and meat products	High intensity US, High pressure processing, UV	*E. coli*, *L. monocytogenes*, *S. aureus*, *B. cereus*, *Clostridium botulinum*, *Clostridium difficile*, *Clostridium perfringes*, etc.
Fish and sea foods	UV, PL, US, high pressure processing, and nonthermal plasma	Total aerobic psychrotrophic and mesophilic bacterial count, *L. innocua*, *L. monocytogene*

academic researchers and food engineers/scientists to further bridge the gap between academic research and industrial applications, especially in the area of heating. An optimum parameter for the treatment of food is required for each of the technologies reviewed, and this prompts future investigation and optimization as a function of food type and composition. Furthermore, increasing the shelf lives of food items without compromising the original food properties has become a critical concern. Hence, future studies are recommended in this area to tackle this challenge.

AUTHOR CONTRIBUTIONS

Helen Onyeaka conceptualized the study. The initial draft was written by KeChrist Obileke, Taghi Miri, Ozioma Forstinus Nwabor, Abarasi Hart, Zainab T. Al-Sharify, and Shahad Al-Najjar were involved in data curation and analysis. Christian Anumudu, and KeChrist Obileke were involved in editing the manuscript and referencing. All authors were involved in the preparation and review of the manuscript jointly contributed to writing the entire manuscript.

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DATA AVAILABILITY STATEMENT

No data available

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