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Review

Advanced Technologies in Food Processing—Development Perspective

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Abstract: Research into innovative techniques in food technology is developing dynamically. This is indicated by the significant increase in the number of scientific studies in this field. The aim of this work was to provide a comprehensive, in-depth analysis of the available scientific evidence on new techniques used in food that not only increase efficiency but also enable the creation of products with desirable sensory and nutritional characteristics. Research on techniques including cold plasma, high-pressure processing, ultrasound, pulsed electric fields, sous vide, and microwave heating aims to provide innovative methods of food processing, in the context of meeting growing consumer expectations and optimizing production processes in the food industry. Compared to traditional food processing methods, innovative techniques can provide more efficient solutions in the processing of products. Research on alternative non-thermal methods in food technology suggests their possible benefits, including enhancing sensory and nutritional quality, minimizing environmental impact, and increasing production efficiency, which are a significant challenge in the modern food industry. Despite the many benefits, it is worthwhile to continue research to further improve modern food technologies.

Keywords: advanced food technologies; cold plasma; high-pressure processing; ultrasound; pulsed electric fields; food quality; food safety; food processing

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1. Introduction

The dynamic development of the food industry, as one of the most important sectors of the economy, forces the introduction of new technologies. Modern technologies are becoming a key element of the sector, introducing innovations that not only increase production efficiency but also shape new standards of food quality and safety [1]. Traditional food processing has many disadvantages, such as high energy consumption and waste management. The use of conventional techniques can lead to negative effects such as solvent contamination and food degradation. This is why more and more food producers are faced with the challenge of finding more environmentally friendly ways of processing food. In the food industry, non-thermal technologies are used for various purposes, such as preservation, disinfection, shelf life extension, or food modification. However, it is important to match the appropriate non-thermal technology to the specific type of food while optimising the process for its needs [2,3]. Investments in new technologies can help manufacturers increase production efficiency and improve product quality [4]. Recently, many new food processing technologies have appeared, such as high-pressure processing, ultrasound, pulsed electric fields, cold plasma, sous vide, and microwave heating [5–10]. Among the new, unconventional food preservation technologies, the non-thermal high-pressure method seems to be promising. The use of high-pressure processing (HPP) allows us to inactivate pathogenic micro-organisms, such as *Salmonella* and *E. coli*, particularly in the meat industry, to ensure safety and minimise adverse sensory changes such as loss of taste, colour, or texture of meat products [11]. The use of cold plasma in food production allows us to extend the shelf life of food products and improve their quality and safety. It can be used, for example, to fix a variety of food products, such as fresh fruit and vegetables, without increasing their temperature or causing adverse temperature changes [12]. One of the innovative and developing technological solutions in recent years is the application of ultrasound in food processing. The use of ultrasound can lead to a shortening of the drying time and temperature, thereby improving product quality while preserving health-promoting compounds. Recent studies show a continuous improvement of ultrasonic techniques, which effectively increases the drying time of food products, e.g., fruits, whose contribution is particularly important in our diet [13]. Another modern non-thermal method of food processing used in the food industry is the pulse electric field (PEF). The pulsed electric field has been used, among others, in the production of juice, milk, eggs, and vegetables. This process has many advantages, such as retaining more nutrients compared to traditional pasteurisation methods, increasing the shelf life, and improving the texture of the products. However, there are also many challenges associated with the application of PEFs, such as the need to determine the optimal process parameters for each type of food [14]. These methods not only make it possible to obtain food with a long shelf life, safe for health and without added preservatives, but are also more environmentally friendly than conventional methods [15]. An in-depth analysis of the current knowledge of advanced food processing technologies seems crucial, given the intensive development of new technological solutions in this industry. The dynamic growth of the use of new techniques in food technology can be seen from the number of publications typing the term "new techniques in food technology" into the Pubmed search engine, which indicates the growing interest of scientists and the food industry on this topic and the possibility of introducing innovative solutions in food production and processing. A significant intensification of research in this field can be observed in recent years (Figure 1).

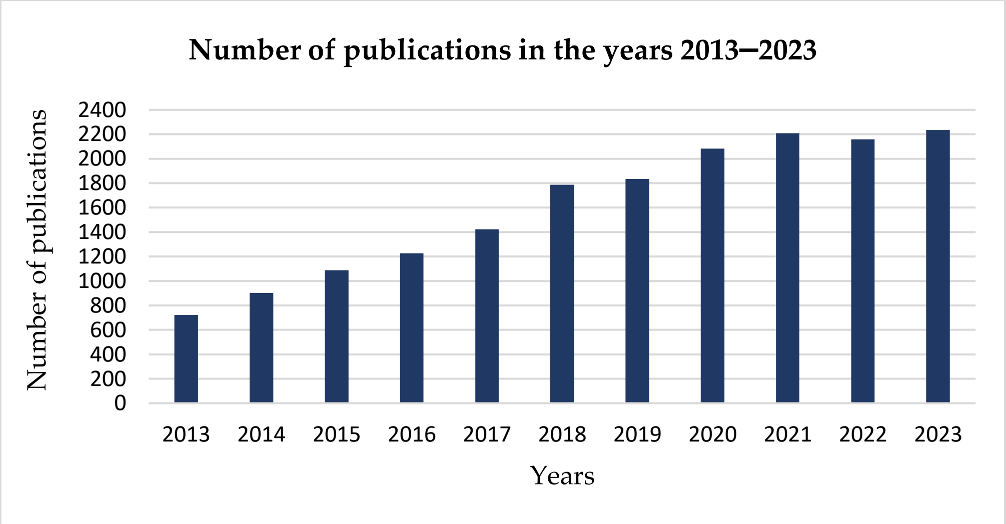


Figure 1. Number of publications retrieved by searching the term "new techniques in food technology" in the Pubmed database from 2013 to 2023. Search conducted on 19 April 2024.

Innovative techniques used in food technology can improve food quality and production efficiency, but they must meet the appropriate standards for their industrial application. The aim of this review was to analyse the available information on the benefits and potential risks of using innovative techniques in the field of food technology.

When writing this systematic review, the following aggregators of scientific journals were used: MDPI, PubMed, ScienceDirect, and Web of Science. Scientific articles were searched using the following keywords: advanced food technologies; cold plasma; high-pressure processing; ultrasound; pulsed electric fields; food quality; food safety; and food processing. Research papers from 2013 to 2023, including original research and review articles, were analysed. Publications that were published in English and met the inclusion criteria set out below were included in this review. Research publications containing information on innovative techniques in food technology such as cold plasma, high hydrostatic pressure, ultrasound, electric field technique, sous vide, and microwave heating were included. The analysis of available scientific evidence was prepared in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist.

2. Application of Non-Thermal Plasma in Food Technology

Among the new, unconventional techniques used in food technology, the cold plasma method is becoming increasingly important. The term "plasma" was first used by the American physicist Irving Langmuir in 1928 [16]. Plasma, also known as the fourth state of concentration, is an ionized gas, such as air, oxygen, nitrogen, and argon, which is formed by adding enough energy to it to break down its particles into electrons and ions. Concentration states of matter (solid, liquid, gaseous) have lower energy potential compared to plasma. It also includes electrons, free radicals, excited particles, and photons [17]. A distinction is made between high-temperature plasma, which occurs in the interior of stars, and low-temperature plasma, which is used in food technology due to its much lower temperature ranges [15]. Food preservation aims to prolong its shelf life by inactivating micro-organisms, including pathogenic ones. Previous studies have shown that cold plasma can neutralize pathogenic micro-organisms, including bacteria, viruses, pathogenic fungi, and parasites [10]. There is a need for a broader understanding of the mechanisms of virus inactivation using cold plasma technology. Many studies report that cold plasma causes the breakdown of proteins and nucleic acids, interfering with the structure of the virus [18,19].

The source of microbiological contamination of fresh vegetables and fruits stems from several pathogenic micro-organisms such as *Salmonella*, *Listeria monocytogenes*, and *Eschericha coli*. Some strains of *E. coli* can cause disease and lead to severe diarrhoea. There is now an increased incidence of serious gastrointestinal diseases, with around 1.7 billion people suffering from severe diarrhoea every year. Acute diarrhoea has become one of the leading causes of death in children under 5 years of age [20]. According to EFSA reports, *Salmonella* poses a serious threat to human health due to foodborne pathogenicity. Statistics report that *Salmonella* is the cause of more than 150,000 deaths worldwide [21]. The contamination of food with pathogenic micro-organisms endangering human health is a starting point for the design and potential use of new techniques in the food industry that meet the criteria of safe food. Cold plasma processing technology contributes to improving the nutritional quality of food. A study on such technology was carried out by Lee et al. (2015), who assessed the efficacy of microwave-assisted cold plasma technology for enhancing the microbiological safety of both dried fruits and fresh vegetables. Cold plasma inactivated *Salmonella typhimurium* that was inoculated on cabbage and lettuce, with the inactivating agent being nitrogen, a plasma-forming gas. They also used a mixture of helium and oxygen gas to inactivate *Listeria monocytogenes* [22]. Studies of the effects of cold plasma on microbial elimination suggest that the degradation of membrane proteins and lipid oxidation are directly related to the high reactivity of the oxygen and nitrogen derivatives of cold plasma. Further research is needed to accurately verify this innovative technology in order to improve and optimise plasma systems [23].

The inactivation of pathogens is also shown by other scientific studies describing the use of plasma technology in a wide range of food products, namely fruits (apples, berries, dried figs), vegetables (tomatoes, lettuce, cabbage, and potatoes), seed sprouts, and almonds [24,25].

The extraordinary effectiveness of plasma technology in reducing the number of pathogens on Golden Delicious apples was also confirmed. *Salmonella typhimurium*, *Salmonella choleraesuis*, and *Escherichia coli* were inactivated from the surface of the fruit using atmospheric cold plasma. Cold plasma technology was used to inactivate microbes using nitrogen and ultraviolet photons. The authors concluded that the effectiveness of cold plasma is determined by the time of action and the composition of the inactivating agent. Further, an in-depth analysis of a larger pool of food products should be carried out in order to bring the technology to the commercial market [26].

Technological processes that reduce pathogens such as *Salmonella* on polyethylene terephthalate (PET) packaging demonstrate that cold plasma disinfection allows microbiologically safe packaged fresh food to be obtained [27]. This process eliminates re-contamination after food processing [28].

However, in order to establish an effective dose, but without adverse effects, it is also necessary to continue studies on the potential formation of toxic compounds via cold plasma treatment due to the potential adverse effects of improper cold plasma treatment on the physicochemical properties of food [29].

2.1. Extraction of Bioactive Compounds Using Cold Plasma

Currently, there is an increasing interest in the bioactive compounds in food, as non-communicable diseases have become one of the biggest health problems of highly developed countries. Due to environmental pollution, stress, poor nutrition, and lack of regular physical activity, there is a global epidemic of diseases such as overweight, obesity, cardiovascular diseases, cancer, diabetes, and allergies. Food rich in bioactive compounds shows positive effects on human health [30].

Understanding the effects of cold plasma on bioactive food compounds provides the basis for advancements in the use of this technique to increase the efficiency of the extraction process and the quality of the final product [31]. Traditional food preservation methods, commonly known as heat treatment, reduce the bioavailability of some nutrients and worsen the organoleptic properties of products exposed to high temperatures, e.g., during cooking. Given the destructive nature of heat treatment for sensitive food ingredients such as vitamins, antioxidants, carotenoids, and anthocyanins, it seems appropriate to use innovative techniques to preserve thermolabile bioactive compounds [32]. The use of cold plasma as a pre-treatment prior to the extraction of bioactive compounds can help to improve the extraction efficiency, reduce the extraction time, increase the yield of extracts, and increase the stability of bioactive compounds. Sruthi et al. (2022) demonstrated that cold plasma inactivates numerous enzymes, including polyphenolic oxidase and peroxidase, thereby preserving the nutritional value of the food tested. However, in order to scale up the cold plasma technique to commercial production, it is necessary to carry out more extensive and in-depth scientific studies to verify the safety of its use [33].

Another study from 2021 carried out to determine the effect of cold plasma on the chemical structure of different food components showed a higher extraction efficiency of cold plasma bioactive compounds. Twelve herbal extracts (*Echinacea purpurea*; *Salvia officinalis*; *Urtica dioica*; *Polygonum avculare*; *Vaccinium myrtillus*; *Taraxacum offici-nale*; *Hypericum perforatum*; *Achillea millefolium*; *Sanguisorba officinalis*; *Leonurus hearta*; *Ballota nigra*; *Andrographis paniculata*) were subjected to cold plasma pre-treatment with nitrogen. Numerous parameters were evaluated, including antioxidant activity, antioxidant content, pH, and colour. Extracts treated with cold plasma were characterized by a higher content of bioactive compounds, e.g., polyphenols and anthocyanins. The use of the cold plasma technique for the extraction of raw materials of a vegetable origin, due to the lower proportion of volatile compounds in the final product, is an innovative approach applicable to our technology to produce food additives [34].

Similar relationships were found by Silveira et al. (2019) when analysing the effect of cold plasma use time on the bioactive compounds present in a guava-flavoured whey drink. It was shown that with a shorter exposure time to cold plasma, an increase in antioxidant activity (increased concentration of vitamin C and volatile compounds) was observed, with a simultaneous decrease in carotenoid content and a less favourable fatty acid profile. On the other hand, a longer time and higher intensity of cold plasma caused a decrease in vitamin C and volatile compounds, with a higher level of carotenoids. By modifying time parameters and working conditions with the use of plasma technology, variable content of bioactive compounds can be observed [35]. Pankaj et al. 2018 suggested that the ascorbic acid content of fresh fruit treated with cold plasma can be reduced by approximately 4%. A reduction in ascorbic acid was also observed in orange juice that was subjected to cold plasma technology [36]. Similar relationships were observed by Rodriquez et al. (2017), who showed a decrease in ascorbic acid content in cashew apple juice (*Anacardium occidentale* L.) under the influence of cold plasma. These findings suggest that cold plasma has a negative effect on vitamin C content [37].

2.2. Cold Plasma Technology in Drying Pre-Treatment

Drying, as one of the oldest food processing methods used to extend the shelf life of food, involves the evaporation of water from the product. Food drying techniques aim to obtain high-quality products in terms of organoleptic and sensory parameters such as appearance, taste, colour, consistency, and texture. The choice of the appropriate drying method depends on the type of raw material and the desired end characteristics of the drying, including microbiological, nutritional, physicochemical, and sensory properties [38].

Due to the effectiveness and many potential benefits of cold plasma, it is increasingly used as a pre-treatment method before drying various types of food products. Drying at low temperatures may maintain the initial flavour and colour of the test product, while higher temperatures used in conventional drying techniques may lead to loss of flavour and colour of the final product, thereby adversely affecting the quality of food undergoing traditional drying methods [39,40]. In addition, conventional high-temperature drying methods require more energy and time, while reducing the nutritional value of food by degrading nutrients such as vitamins, proteins, and fatty acids. Cold plasma technology has been shown to improve the drying rate [41]. Furthermore, it facilitates a reduction in drying time by decreasing the moisture content on the food’s surface, thereby enhancing the efficiency of the process [10,42]. A study conducted by Sosnin et al. (2023) proved that employing cold plasma for drying fresh vegetables resulted in a significant reduction in processing time. The experiment has shown a reduction in the drying process by 18.2%, accompanied by decreased energy consumption compared to conventional tomato drying methods utilized in the processing industry [43]. Another example of the effect of cold plasma on the drying process is the study carried out by Nedamni et al. (2022). Apple slices were used and tested in simulations using COMSOL. Two models were made, one of which used cold plasma and airflow. The other one used the classical drying method at 60 °C with laminar airflow. The results of the experiment showed that without the use of air circulation, plasma technology is not efficient enough, while the drying time with the air flow was reduced by about 40% compared to conventional temperature drying. In addition, energy consumption was reduced dozens of times by means of plasma pre-treatment. This technology can effectively improve and reduce the cost of energy consumption; however, research on a wider scale is needed on a variety of food products [44].

The development of new drying technologies focuses on finding alternative preservation methods that will help improve the microbiological stability and shelf life of food products. The use of cold plasma as a pre-treatment step before drying food can have a positive impact on the quality, microbiological safety, and efficiency of the process [39].

Unfortunately, it can negatively affect the composition of the final product. As noted by Seelarat et al. (2023), cold plasma pre-treatment lowers the level of carotenoids in dried jackfruit slices. Nevertheless, as is customary with emerging technologies, further research is necessary to optimise the process specific for food products [45].

2.3. Application of Cold Plasma in the Meat Industry

Meat production is a key aspect of the food economy. The demands of consumers and the food industry force a production of food that is safe and healthy for society. The presence of pathogenic micro-organisms in meat products forces manufacturers to use different methods for disinfecting raw materials. Traditional methods of eliminating microorganisms adversely affect the quality of meat products. Processing and preservation require the use of innovative production techniques, such as cold plasma, to extend the shelf life of a product while preserving its nutritional value and quality [46].

Cold plasma can be used as a pre-treatment process for cold cuts, e.g., before cooking, drying, or preserving. The presented technology allows for a controlled increase in microbiological safety on the surface of meat products. The use of cold plasma to remove unwanted odours, colours, and flavours in sausage products can significantly improve the quality of the final product. Moreover, this method is more environmentally friendly compared to traditional thermal processes, which may contribute to reducing energy consumption and greenhouse gas emissions [47].

A study conducted by Zeraatpisheh et al. (2022) investigated the application of cold plasma for non-thermal cooling of poultry sausage slices before packaging, following processing and cooking. Various samples of the sausage underwent treatment with ultraviolet radiation, cold plasma, and a negative control without any external influence to prevent the growth of pathogenic micro-organisms. After storage for 60 days, the samples were assessed for colour, pH, and peroxide number. No changes in pH and organoleptic parameters were observed, but the content of peroxides was lower in samples treated with plasma compared to those treated with ultraviolet light. This means that the use of innovative technology in the production of meat processing using plasma is effective because the development of microorganisms is limited, which allows the shelf life of products to be prolonged [48].

Cold atmospheric plasma exhibits the strongest antimicrobial and antiviral activity on the surface of the meat product tested, thereby effectively reducing the number of pathogens on the surface of the fresh or processed meat product [49]. Yadawa et al. (2019) provided information on the potential use of cold plasma in the processing of ready-to-eat cold cuts. Depending on the duration of the cold atmospheric plasma action on the raw material, significant inactivation of *Listeria innocua* was observed in the tested meat product. This indicates the possible use of cold plasma in minimising the number of micro-organisms on the surface of food [50]. It is worth noting that the cold atmospheric plasma technique, despite its great popularity, is currently in the testing phase. In the absence of reliable information on the elimination of pathogens, it is not possible to unequivocally confirm the efficacy of this technique regarding the preservation of the nutritional value of meat products [51]. Cold plasma is thought to accelerate lipid oxidation. Pérez-Andrés et al. (2020) investigated the effects of cold plasma treatment on the lipid balance in different meat models (pork, chicken breast, beef, and lamb) and found no differences in lipid and cholesterol. Moreover, treatment with cold atmospheric plasma did not cause any discoloration of the tested meat raw materials. In addition, it is necessary to carry out more extensive analyses to determine the precise parameters of the cold plasma, which will accurately demonstrate its optimal operating conditions while maintaining the quality parameters of the products [52].

A recent study by Varilla et al. (2020) highlighted the need to improve cold plasma technology due to the potential for adverse effects on the sensory characteristics and nutritional values of processed foods. Lipid oxidation has been observed in meat and fish due to the presence of reactive oxygen forms in a cold plasma-controlled atmosphere, accelerating the oxidative rancidity process, which in turn degraded the quality of the products and shortened their shelf life [53]. However, it is worth noting that cold plasma is a relatively new technology, and studies are currently underway on its effectiveness and safety in the context of food production. Appropriate examinations and tests must be carried out prior to the possible use of this technology in meat processing to ensure that it does not adversely affect the quality and safety of the final product [47].

3. High Pressure Method in Food Technology

Consumer demand for safe, healthy, and high-quality food has contributed to the development of new non-thermal technologies. In the 20th century, the first mention of high-pressure technology appeared in the letter tour, whose forerunner was Professor PW Bridgman. In the 1990s, meat products such as cooked hams and sausages, fruit jams, retort rice products, and soy sauce were the first commercially available high-pressure products [54]. High hydrostatic pressure (HHP) is an innovative, unconventional method of food preservation that has been applied in the food industry. This process helps to increase food safety, prolong its shelf life, and maintain the highest organoleptic quality. Products treated with high hydrostatic pressure are of superior quality due to the lack of heat treatment, which preserves higher nutritional value and sensory quality. This stands in contrast to traditional thermal food processing methods, which degrade nutrients and impair organoleptic characteristics such as taste, colour, and odour [55]. A very good example of the application of the HPP method is in the processing of vegetables and fruits. On the one hand, it helps to preserve the final product (e.g., fruit juice) from microbiological contamination, while, on the other hand, it maintains high-quality sensory characteristics. However, the high-pressure technique is used to prolong the shelf life of many food products. HPP can reduce the number of pathogens and inactivate enzymes affecting the shelf life of food. As an example, rice products obtained with HPP have a better texture by saturating grains with water [54,56]. Moreover, a study carried out by Gowaris et al. (2021) showed that innovative high-pressure techniques can inactivate even viruses with little effect on the physicochemical parameters of food products. HPP has been shown to effectively limit the development of viruses, such as hepatitis A, rotaviruses, and noroviruses, which are foodborne pathogens commonly found on vegetables and crustaceans. As higher virus survival is observed in foods with higher moisture content subjected to high-pressure techniques than in foods with lower water activity, further scientific analysis is necessary to assess the appropriate conditions for high-pressure technologies for the inactivation of foodborne viruses [57]. High-pressure technology is also used in the dairy industry as an alternative method for milk pasteurisation. Many studies showed the potential use of HPP to destroy pathogenic micro-organisms such as *Listeria monocytogenes*, *Staphylococcus aureus*, and *Listeria innocua*. Studies showed that milk subjected to high pressure (400 MPa) does not affect the loss of B vitamins, e.g., B1 and B6 [58]. Additionally, subjecting fresh milk to the HPP technique helps maintain its microbiological safety. Lim et al. (2023) concluded that subjecting fresh high-pressure cow's milk (600 MPa) to treatment did not result in significant changes in its vitamin and mineral content. Milk treated with HPP retained calcium (99.3%), magnesium (99.1%), and phosphorus (99.4%). On the other hand, milk subjected to high pressure and stored for two months exhibited an 85% decrease in vitamin C, an 80% reduction in vitamin B6, and a 91% decrease in vitamin B3 content compared to traditional pasteurisation methods [59]. In addition, there is an increase in the number of scientific studies on the use of innovative high-pressure technology for the pasteurisation of human milk. The study carried out by Pitino et al. (2019) showed that using the HPP method resulted in the lowest reduction in bioactive components in breast milk. Specifically, lysozyme activity remained unchanged when it was subjected to high pressure, whereas it decreased by approximately 44% under rapid heating conditions. Similarly, lactoferrin experienced a 74% decrease after heating, whereas only a 25% reduction was observed when employing the HPP method. For these reasons, future studies on the introduction of high-pressure technology for the preservation of breast milk may be more effective than traditional pasteurisation in preserving the nutritional composition of milk [60].

Removal of toxins and prevention of their formation in food products are also recognised as important food safety benefits of using HPP. Research into the impact of high-pressure processing on natural food allergens to reduce their negative health impacts is a promising area of research aimed at producing fresh and allergen-free food products. High-pressure technology is an important non-thermal processing tool used to obtain slightly processed but healthier food products compared to other processing technologies [61]. Hurtado et al. (2017) confirmed that non-thermal pasteurisation with HPP (350 MPa) may be an effective alternative to traditional thermal treatment to preserve the freshness and nutritional value of fruit products. Despite some sensory and nutritional losses during storage, the benefits of using HPP may outweigh these losses, especially for consumers seeking products with the highest possible health and sensory properties. Further studies are needed to optimise HPP processes for fruit-based cocktails [62]. The high-pressure technique has also been applied in the processing of juices. The HPP method was compared with the preservation of food at high temperatures but in a short time. Tomato juice subjected to high-pressure peeling exhibited a higher concentration of β-carotene and lycopene compared to the one processed using thermal techniques. Unfortunately, higher values of aldehyde compounds were observed with high-pressure treatment [63]. The analysis by Sanches et al. (2014) compares the treatment of six vegetables (tomato, broccoli, green pepper, spinach, red pepper, and carrots) using high-pressure and high-temperature techniques to the amount of cardboard and chlorophyll dyes. Chlorophylls subjected to heat treatment rather than high-pressure treatment were significantly degraded [64].

Marszałek et al. (2015) showed that high-pressure treatment (500 MPa) resulted in complete degradation of vitamin C in strawberry puree. In addition, a decrease in anthocyanins of about 70% was detected during 12 weeks of storage [65]. Similar losses of anthocyanins were observed after the application of high pressure (400 MPa) in the study of Deng et al. (2019). HPP is a forward-looking solution, but more research on other products should be carried out so that the results of the impact of the innovative HPP technique can be brought to the commercial market [66]. The analysis of pathogens in cream showed an improvement in the product's quality characteristics. When comparing high-pressure technologies, such as non-thermal treatment, with the conventional high-temperature pasteurisation method, it was found that HPP (450-600 MPa) extended the shelf life of cream to approximately 50 days. Moreover, the use of high-pressure technology resulted in a reduction in the presence of pathogenic micro-organisms, such as *Listeria innocua* and *Escherichia coli* [67].

The reduction of phenolic compounds after storing food that was subjected to high-pressure techniques may be due to the insufficient removal of oxidizing enzymes during improper heat treatment. It is important for producers to find the right balance between the preservation of polyphenols and the durability of their products. Further studies are recommended to investigate the impact of both technologies on different types of polyphenols as well as bioavailability and biological activity [68]. The high-pressure processing of food offers numerous advantages, including longer shelf life, retained nutritional value, absence of preservatives, and preservation of natural flavour and aroma [69]. This method has become increasingly popular in the food industry, especially in the production of items such as juices, meat, or ready meals [70].

4. Application of Ultrasound in Food Processing

Nowadays, ultrasound is widely used in the food industry. It is considered to be a promising technique for increasing process efficiency while maintaining the quality of food products [71]. Numerous studies showed the potential possible benefits of using ultrasonic technology in optimizing food-freezing processes. Freezing is one of the most effective techniques for the long-term storage of perishable foodstuffs, while allowing them to be reprocessed. The size and distribution of ice crystals are key parameters in the context of frozen foods, and numerous studies have been carried out focusing on these aspects [72]. The ultrasound-assisted freezing process has been proven to effectively increase the freezing efficiency while promoting the formation of small and evenly distributed ice crystals, which can positively affect the quality of frozen products [73]. This effect translates into an improvement in the quality of stored food. The search for innovative freezing techniques can effectively increase the efficiency of the process, given the low efficiency of conventional freezing methods [74]. Ultrasound accelerates the freezing process of food products, such as fruits (apples) and vegetables, including potatoes and broccoli [75]. Additionally, Hu et al. (2013) proved that the rate of freezing the dough using ultrasound was increased, and with the use of ultrasonic power of 288 W or 360 W, the total dough freezing time was significantly reduced by more than 11% [76].

Ultrasound is utilized in the thawing of food as well. The thawing process is characterized by long-term action, but suboptimal methods can promote the development of micro-organisms and thus negatively affect the quality of frozen food. However, the defrosting of food products using ultrasound has some limitations due to the shallow penetration depth and point heating. Nevertheless, the use of ultrasound in the thawing process of Pacific cod has shown that in the temperature range of −29 to −1 °C, the process efficiency increased by approximately 71% when employing a frequency of 1500 Hz and 60 W [73].

Ultrasonic technology has also been applied in the meat industry. Ultrasound has a beneficial effect on accelerating the maturation of meat, affecting the increased shelf life of meat products. This technique does not adversely affect the overall quality parameters of the meat products. In the context of meat processing, ultrasound can potentially aid the drying, curing, and marinating process to avoid microbial development and re-contamination of meat [77]. Ultrasound technology can be used to inactivate pathogens such as *Salmonella* and *Escherichia coli*. Al-Hilphy et al. (2020) found that ultrasonic treatment can be successfully applied to improve the texture of chicken meat [78]. Additionally, ultrasound facilitates cleaning of mould and improve sterilization of equipment surfaces, which affects the hygiene and safety of production. However, despite the promising benefits, further studies are needed before ultrasound can be fully implemented in the meat industry to understand and optimise the processes and to assess the impact on the overall quality parameters of meat products [79].

Ultrasound has also been applied in the drying process. Conventional drying methods have some limitations due to low process efficiency, prolonged drying time, and as they adversely affect the sensory and nutritional quality of products. The use of ultrasound as an alternative method of drying food, e.g., vegetables and fruits, seems to be justified due to low energy consumption, shorter drying time, and the possibility of obtaining high-quality drying [8]. The use of ultrasonic technology for the extraction of bioactive compounds from fruits results from its ability to increase water transport [80]. The ultrasound-assisted fruit-drying process involves several methods, including probe and bath sonification, ultrasonic method, and air ultrasound. Bath and probe sonication are used for pre-treatment, utilizing water, osmotic solution, or other solvents. This process entails subjecting the fruit to ultrasound, followed by immersion in a liquid and subsequent drying with air or another conventional method. In contrast, air ultrasound is utilized continuously throughout the drying process [81,82]. According to Fernandes et al. 2023, pre-treatment using ultrasonic technology combined with air drying facilitated the production of dried apples (*Malus domestica*) and jackfruit (*Artocarpus heterophyllus*) supplemented with *Lactobacillus casei*. The high efficiency of the applied technique was reflected in the reduction of the drying time [13].

It is worth mentioning that there is not enough scientific evidence confirming the positive effect of ultrasound at frequencies higher than 100 kHz. In addition, high-pressure conditions can lead to the accumulation of radicals, which can react with food products, causing their degradation. For these reasons, further research is needed to improve this technique to ensure its effectiveness in practice [83,84].

5. Food Processing Using Electric Field Technology

Pulsed electric field processing in food is a technology in which food is subjected to a short-term high-voltage electrical pulse. These impulses cause transient structural changes in the cells, which can lead to the inactivation of micro-organisms and enzymes, positively affecting the shelf life of the product. The process can be used in a variety of ways, such as for drying, pasteurisation, disinfection, reduction of microbial growth, or improvement of product shelf life. Electric field treatment can be applied to different types of food, such as fruit juices, milk, meat, or vegetables. Exposure to high voltages causes the destruction of micro-organisms, which may result in an increase in the shelf life of the product [85]. Roobaba et al. (2022) determined that initial treatment with a pulsed electric field of the product contributes to improved enzyme activation. Food processing by means of a pulsed electric field improves the preservation of vegetable and fruit juices. The combination of pulsed electric field treatment (25 kV) and ultrasound (24 kHz) showed reduced enzyme activity in raspberries and berries [86,87]. The benefits of using pulsed electric field-assisted drying include the maintenance of physicochemical parameters, the colour of the dried products, and the stability of the chemical compounds. In addition, the pulsed electric field-assisted drying process promotes efficient hydration and improves drying kinetics, which is an important factor affecting the final quality of the product. As a result, electrically assisted drying is an innovative alternative to produce products with excellent sensory properties and a longer shelf life compared to traditional drying methods [88].

The pulsed electric field, being a modern food technology, offers unique opportunities to influence the structure and properties of milk and dairy products. Utilizing gentle heating through pulsed electric field treatment technology has helped to increase the safety of milk and milk products. It is worth noting that such treatment is characterized by minimal impact on compounds of significant technological importance, such as protein or nutrients, especially vitamins. The pulsed electric field treatment process significantly improves the shelf life of milk and dairy products [89]. This technique has also been used in the meat industry. In a study by Bhat et al. (2019), the effect of the pulsed electric field on the amount of sodium in the production of meat products was determined. The analysis used samples of dried beef with the addition of NaCl. The obtained results showed a significant impact of pulsed electric field on parameters, such as product strength, which was also confirmed via a sensory evaluation. The effects of the pulsed electric field on the dried beef samples did not change the quality parameters based on oxidative stability. However, the amount of sodium in the sample under the influence of the pulsation electric field decreased. The obtained results suggest that the use of this innovative non-thermal treatment of meat may be an effective method for reducing the amount of sodium in meat products [90]. When studying the effect of the pulsation electric field on the quality of lamb, it was observed that after a storage period of 7 days, the proportion of fatty acids decreased with a simultaneous increase in the amount of amino acids [91]. The pulsed electric field treatment process ensures that nutrients are better preserved, which translates into higher product quality. This innovative technology is highly regarded for its efficiency, no need for high temperatures, safety, and environmental friendliness, which makes it increasingly used in the food industry. In contrast, pulsed electric field treatment processes underline the need for a balanced approach due to additional studies to fully understand the impact of pulsed electric fields on food and nutrition security [14].

In the food industry, there is considerable interest in PEF technology due to its efficiency, non-thermal nature, cleanliness, and ecological approach to preservation while maintaining freshness. Although there are studies on enzyme deactivation using PEF, as well as on the stability of enzyme parameters, there are few compounds on these issues, which justifies the need for further studies in the future [86].

6. Other Innovative Ways to Heat Food

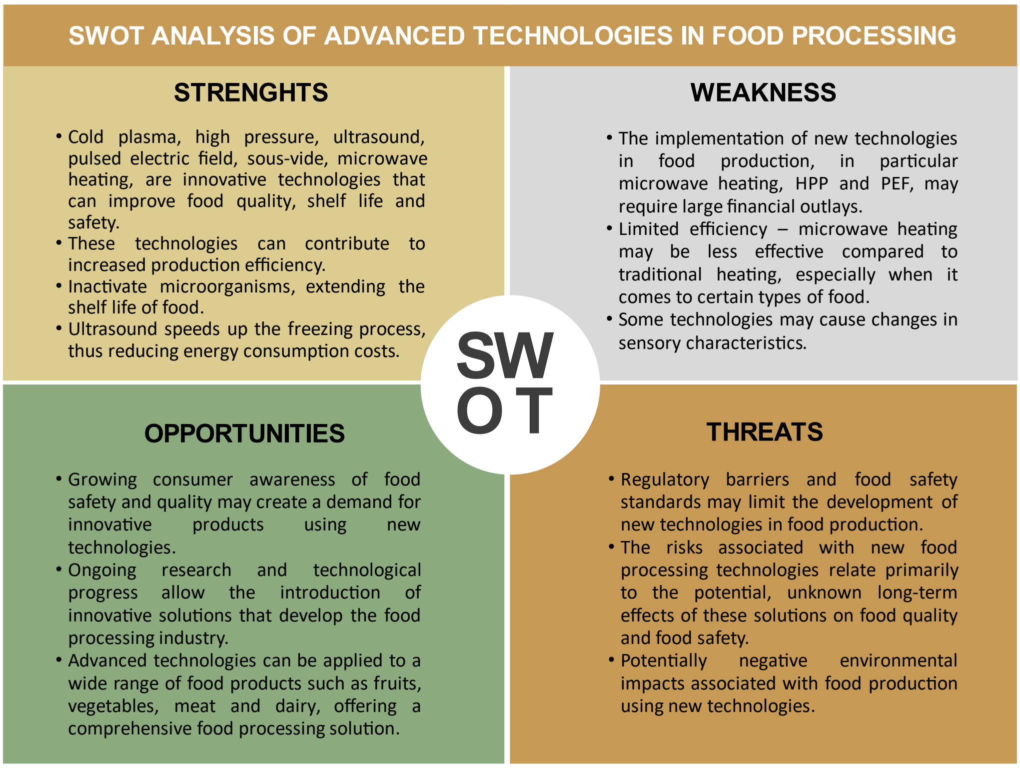
The sous vide technique is based on the preparation of dishes by cooking at a low temperature in a vacuum. Raw or partially cooked ingredients are packed in sealed plastic bags, which are then gently cooked in a water bath at a fixed temperature of 65 to 95 °C [92]. The use of sous vide technology has many advantages, such as the preservation of the quality and sensory properties of food. Thanks to precise temperature control, perfect cooking can be achieved. Vacuum bags also allow for extending the shelf life and improving the taste and nutritional value of food products. However, it should be kept in mind that the low temperatures used in this method may give rise to microbiological risks related to an incorrect pasteurisation process, which in turn may pose a risk to the health of consumers and shorten the shelf life of food products [93]. An analysis by Kosewski et al. (2023) compared conventional cooking, steaming, and sous vide techniques [94]. Studies were performed on, among others, spinach, artichoke, white artichoke stalk, red artichoke stalk, root parsley, carrots, green peas, pumpkin, asparagus, asparagus beans, brussels sprouts, broccoli, cauliflower, and red cabbage [95–102]. A study comparing the effects of sous vide and steamed and conventional cooking on vitamin C retention in eight different vegetables showed that sous vide causes less vitamin C loss due to lower temperatures and lack of oxygen during the process. Vitamin C is known to decompose rapidly at high temperatures, so sous vide has been shown to be more beneficial for preserving the nutritional value of vegetables in some cases compared to steaming and conventional cooking [103]. For example, during sous vide cooking, the percentage decrease of vitamin C for cauliflower was 19.9%, 47.1% for steaming, and 48.7% for conventional cooking [102]. In the case of sous vide cooking broccoli, the decrease was 35.4%, in the case of steaming, it was 41.8%, and in the case of conventional cooking, the decrease was 58%. However, in another case of asparagus cooking, the conventional cooking technique performed best, and the reduction of vitamin C was 1.22% lower than for sous vide cooking by 3.66% [100]. In addition, the sous vide technique is used in the thermal processing of seafood. A study by Russo et al. (2023) showed that cooking mussels at temperatures above 80 °C effectively inhibited the growth of mould and yeast and of *Pseudomonas* spp. Moreover, no potential pathogens such as anaerobic sulphite-reducing *Clostridia*, *Listeria monocytogenes*, and *Salmonella* have been identified [104].

The next modern method of food heat treatment is the use of microwave technology, characterized by fast and efficient heating, minimized energy consumption, and intuitive control. Thanks to their ability to penetrate deep into the structure of food, microwaves allow for the creation of dishes with excellent taste and appearance. In addition, they support the absorption of nutrients and accelerate the metabolism of active substances [105]. Microwave heating, unlike traditional thermal methods, retains a higher number of bioactive compounds, showing a stronger antioxidant effect. These benefits are mainly due to the short treatment time and the absence of water during the process, which protects the bioactive substances from leaching [106]. A study has shown that the preparation of beef using a microwave oven may be healthier as it contains less harmful compounds, such as volatile N-nitrosamines and polycyclic aromatic hydrocarbons, compared to traditional frying or grilling methods [107]. However, the use of microwave heating can lead to uneven heating of meat due to differences in its thickness and shape. To investigate this phenomenon, a test was carried out in which microwaves of a frequency of 2450 MHz and a power of 500 W, which were directed at whole carcasses of chickens for 5 min. As a result, temperature variation was observed between different parts of the meat, where the temperature of the breasts oscillated between 15 °C and 45 °C compared to the thighs [108].

7. SWOT Analysis

In this review, we included SWOT analysis (Figure 2) to better present new technologies, their potential benefits, and challenges. The illustration shows the strengths and weaknesses as well as opportunities and threats of technological innovation in food production. The results show that new technologies can bring many benefits over traditional methods, especially in terms of production efficiency, waste minimisation, and environmental protection. Their implementation can help to increase productivity, improve product quality, and maintain food security [109].

The conclusions of the SWOT analysis show that modern technologies in food production have many advantages, such as improved quality and shelf life, increased production efficiency, and inactivation of micro-organisms. In particular, the technology used for cold plasma, HPP, and ultrasound has successfully found its application in the fight against harmful micro-organisms [110–112]. Innovative technologies, such as pulsed electric fields, have low energy consumption during food processing, which is another advantage they have over traditional methods [113]. However, there are also weaknesses, such as the high costs of implementing new technologies, the limited effectiveness of some of them, and the lack of sufficient scientific evidence for their effectiveness. In addition, it is worth noting that new technologies such as cold plasma change the sensory characteristics of products, such as colour or texture, and thus may influence consumer behaviour, which is manifested by the varying acceptance of products treated with these techniques [114]. The opportunities for technological development are linked to growing consumer awareness and technological progress, which may create demand for innovative products. Some technologies such as sous vide allow for efficient processing of seafood due to the low degree of interference with its structure. This will allow food manufacturers to obtain high-quality products [115]. Risks arise from regulatory barriers, potential long-term effects on food quality and safety, and negative environmental impacts associated with food production using new technologies. Therefore, it is necessary to conduct further studies and monitor the impact of these new technologies on food production in order to guarantee the safety and quality of food products. For instance, it is important to investigate any changes in the sensory characteristics of products treated with microwaves or ultrasound [116]. For these reasons, it is necessary to continuously monitor the impact of modern technologies on food production in order to minimise potential risks to food quality and safety. It is also necessary to increase research in this area in order to assess the impact of new technologies more effectively. It is also important to educate consumers about the advantages and risks of modern technologies in food production so that they can make informed decisions about the purchase and consumption of food products. This will ensure that modern technologies are used responsibly and to the benefit of all parties involved in the food production process [117].


SWOT ANALYSIS OF ADVANCED TECHNOLOGIES IN FOOD PROCESSING

STRENGHTS

- Cold plasma, high pressure, ultrasound, pulsed electric field, sous-vide, microwave heating, are innovative technologies that can improve food quality, shelf life and safety.
- These technologies can contribute to increased production efficiency.
- Inactivate microorganisms, extending the shelf life of food.
- Ultrasound speeds up the freezing process, thus reducing energy consumption costs.

WEAKNESS

- The implementation of new technologies in food production, in particular microwave heating, HPP and PEF, may require large financial outlays.
- Limited efficiency – microwave heating may be less effective compared to traditional heating, especially when it comes to certain types of food.
- Some technologies may cause changes in sensory characteristics.

OPPORTUNITIES

- Growing consumer awareness of food safety and quality may create a demand for innovative products using new technologies.
- Ongoing research and technological progress allow the introduction of innovative solutions that develop the food processing industry.
- Advanced technologies can be applied to a wide range of food products such as fruits, vegetables, meat and dairy, offering a comprehensive food processing solution.

THREATS

- Regulatory barriers and food safety standards may limit the development of new technologies in food production.
- The risks associated with new food processing technologies relate primarily to the potential, unknown long-term effects of these solutions on food quality and food safety.
- Potentially negative environmental impacts associated with food production using new technologies.

Figure 2. SWOT analysis of new technologies in the food industry.

8. Summary

At present, there are promising results indicating the effectiveness of cold plasma in the inactivation of pathogenic micro-organisms. However, there is insufficient evidence for the formation of toxic compounds via cold plasma treatment. This is due to the potential negative impact of improper low-temperature plasma treatment on the physicochemical properties of food. Current scientific evidence suggests that high hydrostatic pressure improves food safety. Still, there is a lack of detailed studies on the impact of high-pressure techniques on different varieties of polyphenols and their bioactivity in food. The use of ultrasound in the food industry is a promising technology that increases the efficiency of the process while maintaining the high quality of food products. It is worth noting that there are research gaps providing information on ultrasound applications at higher frequencies. Another promising method is pulsed electric field treatment, which, due to its ability to inactivate micro-organisms and enzymes, could potentially be used as a tool in various fields of food production, such as drying, pasteurisation, or disinfection. However, there is insufficient scientific evidence on the inactivation of enzymes with the pulsed electric field technique and on the efficacy of the long-term health effects of the pulsed electric field technique. The sous vide technique of cooking at low temperatures in a vacuum has many advantages, such as preserving the quality and sensory properties of food, extending their shelf life, and improving their taste and nutritional value. However, there are potential microbiological risks associated with improper pasteurisation. These methods are promising directions for improving food production processes while maintaining the highest organoleptic quality and nutritional value of food products. Thanks to modern techniques, food can be produced in a more efficient and safe way, which allows us to preserve the high quality and freshness of food products. Although research has progressed in this area, our knowledge is still evolving, which clearly indicates the need for further research in this area. There are still many unresolved issues that require more detailed scientific analysis to understand the potential and possible challenges of applying modern techniques to the food industry. In this context, further development of research is crucial for the effective introduction of innovative technologies into industrial practice, considering both the benefits and the potential risks to public health and the environment.

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