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Effect of Molecular Cooking Techniques on Functional Compounds

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Abstract

The development of technology and current conditions has enabled the diversification of studies on the foods, cooking techniques, and their effects on food composition. One of the emerging cooking methods in this context is molecular cooking, which is applied across various food categories, and offers numerous advantages beyond enhancing the appearance and taste of foods. Techniques such as sous vide, foaming, spherification, use of liquid nitrogen, powdering, flavor-aroma transfer, smoking, gelling, and ultrasonic application techniques are widely used in molecular gastronomy. The application of these cooking techniques can support consumer health by positively affecting the phenolic components and total antioxidant capacity of different foods, as well as promoting innovation in the food industry and presenting foods to consumers with attractive presentations. Moreover, molecular cooking techniques have the potential to innovate and transform the functional compounds of foods, diverging from traditional methods. These changes can significantly impact human health, necessitating a comprehensive evaluation and strategic approaches. This review investigates the effect of molecular cooking techniques on the functional compounds. Recent studies indexed in major databases were analyzed, and the data were systematically organized into tables, offering insights into the role of these techniques in shaping food composition.

Keywords: Bioavailability, Molecular cooking, Functional compounds, Thermal processing, Food processing.

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1. Introduction

In recent times, as a result of technological advancements, lifestyles around the world have changed. Consumers are increasingly focusing on maintaining healthy lifestyles. There is a growing demand for high-quality products that are easy to prepare, fresh, non-sterilized but with extended shelf life, and contain fewer synthetic additives and preservatives (Wereńska, 2024).

Cooking is the process of making food suitable for consumption, enhancing its flavor, and improving its digestibility (Demirel Ozbek et al., 2024). While fruits are typically consumed fresh, vegetables can be consumed both raw and cooked. Thermal processing of food induces various biological, physical, and chemical changes, leading to sensory, nutritional, and textural modifications (Palermo et al., 2014). Moreover, cooking can influence the bioavailability and bioaccessibility of nutrients such as minerals, vitamins, phytochemicals, and fiber (Rinaldi et al., 2021).

Molecular gastronomy, rooted in the contributions of Lavoisier, Brillat-Savarin, and Thomas Graham, was formalized by Nicholas Kurti and Hervé This. It encompasses three key areas: the scientific analysis of culinary techniques, the refinement of recipes for precision, and the exploration of the artistic and social dimensions of cooking (Burke et al., 2016).

Often referred to as a 'scientific approach to cooking,' molecular gastronomy integrates scientific principles into culinary practices. This innovative food movement applies science to cooking, studies flavor through scientific methods, and utilizes laboratory tools to develop advanced cooking techniques (Spence & Youssef, 2018). Unlike traditional food science, molecular gastronomy focuses on the science behind food preparation techniques that can be executed using ingredients readily available in a restaurant or home kitchen. In contrast, food science focuses on large-scale food production, nutrition, and safety. Additionally, molecular gastronomy can include studies on food history and culture (Barham et al., 2010).

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This culinary science is a new discipline within the field of food science, distinguished primarily by its focus on the kitchen, restaurant, and home cooking levels, setting it apart from traditional studies in food science and technology. Collaboration between food scientists, such as food engineers, food chemists, and sensory scientists, and innovative chefs has led to the application of a new cooking approach known as "molecular cooking" or "science-based cooking" (Caporaso, 2021). The global dissemination of flavors and shifting consumer preferences are driving the development of new foods using molecular cooking methods, building on traditional foods (de Jesús Ramírez-Rivera et al., 2023).

Functional foods can be described as industrially processed or natural foods that, when consumed regularly at effective levels as part of a varied diet, have potentially positive effects on health beyond basic nutrition (Granato et al., 2017). For a food to be considered functional, it must contain bioactive compounds, probiotic microorganisms, or prebiotic substances that exert their effects on specific parts of the body (Erbaş, 2006). Functional foods can be naturally occurring, such as iodized salt, which contains functional components. They can also be created by removing certain compounds, such as reducing sodium content in salt (Dayısoylu et al., 2014). Dietary antioxidants, prebiotic substances, probiotic microorganisms, bioactive compounds, and phytochemicals found in foods can be defined as functional components (Erbaş, 2006).

Food processing has been a method used since ancient times to preserve and enhance the nutritional and sensory qualities of food. However, it can lead to nutrient loss and undesirable outcomes, such as changes in color, flavor, or texture, and, in some cases, the formation of toxic compounds. Nevertheless, the benefits of food processing should not be overlooked, as it improves food safety, enhances nutritional value, and promotes the formation or release of functional and bioactive compounds, such as natural phytochemicals (Zhao et al., 2019; Cakir and Helvaci, 2023). Cooking processes can also affect the bioaccessibility and bioavailability of nutrients (Rinaldi et al., 2021).

This study investigates the question, "What is effect of molecular gastronomy techniques on functional compounds?" To address this, a structured approach was employed, focusing on articles indexed in Google Scholar, Scopus, and Web of Science. The search prioritized studies published until 2024, primarily recent English-language articles. The research methodology consisted of identifying molecular gastronomy techniques and analyzing their effects on functional compounds. The relevant techniques included sous-vide, foaming, flavor and aroma transfer, smoking, gelation, spherification, liquid nitrogen, powdering, and ultrasound, and then their impacts on functional compounds such as polyphenols, antioxidants, and vitamins were reviewed using data from the specified databases. General information about the techniques was also compiled to provide context. The collected data on the effects of these techniques on functional compounds were systematically organized into tables for better clarity. This approach aims to offer insights into the role of molecular gastronomy techniques in shaping the functional composition of foods.

2. Sous Vide

Sous Vide technique, which has gained popularity in recent years, is a cooking method frequently used in the production of ready-to-eat foods (Bıyıklı et al., 2020). This technique involves minimal processing technology and has been in use since the 1960s (Hasani et al., 2022; Ayub & Ahmad, 2019). Meaning "under vacuum," this method involves cooking food in heat-resistant, airtight vacuum-sealed bags under controlled temperature (65–95 °C) and time (1–7 hours) conditions (Singh et al., 2023; Kathuria et al., 2022). The desired temperature-time combination for food preparation can be regulated by altering the water bath temperature (53–81 °C) and time (2–48 hours) with water circulation or by circulating heat and steam in convection or combi-steam oven. Heating at low temperatures reduces cooking loss compared to higher temperatures, resulting in a product that retains more moisture (Wereńska, 2024).

The sous vide technique has specific advantages compared to traditional cooking methods (Table 1). This method improves properties such as texture, tenderness, juiciness, color, and flavor of food by allowing more efficient heat transfer from water to food, while also preserving high nutritional value (Bhuyan et al., 2022). Additionally, it prevents oxidative changes (Kathuria et al., 2022). Prolonged low-temperature cooking in Sous Vide improves mineral bioaccessibility compared to other methods, as used in the sous vide technique, provides superior mineral bioaccessibility compared to other cooking methods (Ayub & Ahmad, 2019). Furthermore, this technique helps extend the shelf life of products during storage by preventing the recontamination of frozen foods (Kathuria et al., 2022).

Table 1. Studies on the effects of the sous vide technique on functional compounds

Reference	*Material*	*Method*	*Results*
Florkiewicz et al., 2019	Cauliflower (*Brassica oleracea* var. *botrytis*): white cauliflower and Romanesco cauliflower (green cauliflower), Brussels sprouts (*Brassica oleracea* var. *gemmifera*), and broccoli (*Brassica oleracea* var. *italica*).	The study evaluated whether the sous vide technique could serve as an alternative to traditional cooking methods for Brassica vegetables. The total phenolic content (TPC) was assessed using the Folin-Ciocialteau reagent. The total phenolic content was also determined chromatographically following the hydrolytic procedure of Nardini and Ghiselli.	The study assessed the suitability of sous vide as an alternative to traditional cooking methods for Brassica vegetables, including white cauliflower, Romanesco, Brussels sprouts, and broccoli. Using Folin-Ciocalteu reagent and chromatography, it was found that sous vide preserved vitamin C and stable phytochemicals (e.g., p-coumaric acid) more effectively. The method showed a strong correlation between antioxidant activity, vitamin C, and total phenolic content, suggesting sous vide as an optimal cooking technique for Brassica vegetables.
Rinaldi et al., 2021	Pumpkin (*Cucurbita maxima Duch.*)	The aim of this study was to compare the cooking performance of pumpkin cubes produced using a home vacuum cooking device in terms of texture, color, microstructural properties, antioxidant and carotenoid content, and organoleptic properties with steaming and sous vide techniques. Pumpkin cubes were processed using three cooking methods: sous vide (SV), steaming (ST), and vacuum cooking (VC). Cooking durations were 9 minutes for steaming, 18 minutes for sous vide, and 29 minutes for vacuum cooking. Antioxidant capacity was determined using a DPPH (2,2-diphenyl-1-picrylhydrazyl free radical) test. Carotenoids were analyzed using HPLC.	Significant polyphenol extraction, particularly of gallic acid and naringenin, was observed in pumpkins cooked sous vide and steamed. The total antioxidant activity, attributable to the effects of carotenoids and polyphenols, increased after cooking for vacuum-cooked, steamed, and sous vide samples, respectively, compared to raw pumpkin. Vacuum cooking and sous vide generally outperformed traditional steaming for pumpkin cubes.
Chiavaro et al., 2012	Carrot (*Daucus carota L.*) and Brussels sprouts (*Brassica oleracea var. gemmifera L.*)	Phytochemicals (carotenoids, phenolic compounds, and ascorbic acid) and antioxidant capacity, measured using TEAC (Trolox Equivalent Antioxidant Capacity), FRAP (Ferric Reducing Antioxidant Power), and TRAP (Total Radical Trapping Antioxidant Parameter) analyses, were evaluated in sous vide-processed carrots and Brussels sprouts. The samples were then refrigerated for 1, 5, and 10 days and compared to their raw and oven-steamed counterparts.	Sous vide preparation improved carotenoid, phenolic compound, and ascorbic acid retention in carrots compared to steaming, with minor losses during storage. For Brussels sprouts, sous vide enhanced carotenoid levels but resulted in reduced phenolic and ascorbic acid contents, making it suitable for short-term preservation.
Lafarga et al., 2018	Brassica vegetables, including broccoli (*Brassica oleracea var. italica*) cv. Marathon, Parthenon, broccoli (*Brassica oleracea var. botrytis*) cv. Graffiti, Pastoret, Espigall del Garraf (*Brassica oleracea var. acephala*), and kale cv. Crispa (*Brassica oleracea var. acephala*).	Sous vide processing conditions: 80°C for 15 minutes for florets or leaves and 80°C for 90 minutes for stems. Samples were rapidly cooled to approximately 3–4°C, frozen using liquid nitrogen, and stored at -80°C. Vitamin C content (ascorbic and dehydroascorbic acid) was determined using HPLC equipped with a UV detector. Total phenolic content (TPC) was measured using the Folin-Ciocalteu method. Antioxidant activity was assessed using FRAP (ferric reducing antioxidant power) and DPPH (2,2-diphenyl-1-picrylhydrazyl radical scavenging activity).	The effect of thermal processing on the antioxidant potential, vitamin C, and total phenolic content of various parts of Brassica vegetables, including edible by-products, was evaluated. Both steaming and sous vide significantly reduced vitamin C and total phenolic content in the studied cruciferous vegetables. For most varieties, no differences were observed between samples processed by steaming or sous vide. However, the phenolic content of stems from broccoli cv. Parthenon and Pastoret processed via sous vide was significantly higher than those obtained after steaming. Conversely, a different trend was observed for broccoli cv. Parthenon florets, where sous vide resulted in greater phenolic content loss compared to steaming.

Table 1. *(Continued)* Studies on the effects of the sous vide technique on functional compounds

Reference	*Material*	*Method*	*Results*
Czarnowska-Kujawska et al., 2022	Fresh spinach (*Spinacia oleracea L.*) and broccoli (*Brassica oleracea L. var. italica Plenck*).	The aim of this study was to compare the effects of traditional cooking methods (boiling, steaming, microwaving) with combi oven and sous vide cooking on the organoleptic and health-related properties of spinach and broccoli. To analyze changes in bioactive compounds in raw and thermally processed spinach and broccoli, the total phenolic content (TPC) was determined using the Folin phenol reagent and a spectrophotometric method. The functional properties of the products were characterized by antioxidant activity measured with the DPPH test.	Cooking under sous vide conditions was identified as the most delicate thermal process for preserving phenolic compounds and maintaining high antioxidant capacity in both broccoli and spinach samples. In spinach, DPPH values decreased in the order of raw > sous vide > traditional methods, whereas in broccoli, the DPPH value significantly increased after sous vide processing compared to raw broccoli. Conversely, the DPPH value of broccoli decreased when prepared using traditional methods compared to its raw state.
Kosewski et al., 2018	Green bell pepper, broccoli, beetroot, white onion, and other vegetables sourced from various countries (e.g., Spain, Poland, Egypt, USA) were included in this study	This study compared the antioxidant properties of raw and thermally processed vegetables using traditional and sous vide methods. Antioxidant activity was assessed using the DPPH assay and the FRAP method, measuring the reduction of Fe^{3+} to Fe^{2+}.	A reduction in antioxidative potential was observed for most vegetables after processing compared to their raw state. However, vegetables such as kale, beetroot, red bell pepper, sweet potato, carrot, cauliflower, and kohlrabi showed increased antioxidative potential when processed using the sous vide method. When comparing processing methods, the sous vide method provided greater benefits. Additionally, vegetables like red onion, shallot, broccoli, tomato, parsley root, and cauliflower exhibited higher antioxidative potential after sous vide cooking compared to traditional methods.
Törős et al., 2024	Oyster mushroom (*Pleurotus ostreatus L.*)	This study investigated the effects of sous vide cooking on the antioxidant properties (phenols, flavonoids), activity, and β-glucan content of freeze-dried mushroom samples. Mushrooms prepared for sous vide cooking were vacuum-packed and cooked in three different preheated drying cabinets at 70, 80, and 90 °C for 4 hours. Sous vide-cooked and uncooked samples were freeze-dried and ground into fine powder. Total Phenolic Content (TPC), Total Flavonoid Content, DPPH, FRAP, and β-glucan content were analyzed using HPLC. Total dietary fiber was analyzed using an enzymatic-gravimetric method.	Uncooked mushroom powder exhibited superior antioxidant capacities compared to cooked samples. However, mushrooms cooked sous vide at 80 °C demonstrated the highest total phenolic and flavonoid contents. Additionally, mushroom powder pre-cooked at 70 °C significantly surpassed the uncooked control in β-glucan content. Notably, samples pre-cooked at 80 °C and 90 °C displayed significantly higher total dietary fiber levels compared to uncooked samples.
Guclu et al., 2023	White, orange, and purple sweet potatoes (*Ipomoea batatas L.*)	This study applied three different cooking methods (baking, boiling, sous vide (SV)) to Turkish sweet potatoes of three colors (white, orange, purple) and investigated the effects of cooking methods and tuber color on total phenolic compounds, sugars, antioxidant activity, anthocyanins, and phenolic acids. Total phenolic content (TPC) was analyzed using the Folin-Ciocalteu (FC) reagent. Antioxidant potentials of the samples were evaluated using two methods: DPPH and ABTS. Phenolic compounds were determined using LC-DAD-ESI-MS/MS in negative ionization mode.	Purple sweet potatoes exhibited nearly twice the antioxidant capacity compared to white and orange varieties. Among cooking methods, SV yielded the highest antioxidant capacity for purple-fleshed samples, while baking was most effective for white and orange samples. In terms of total phenolic acid concentrations, orange samples had the highest amounts (up to 263.5 mg/100 g), followed by purple (up to 195.2 mg/100 g) and white samples (up to 133.6 mg/100 g). The highest chlorogenic acid levels were found in baked (80.88 mg/100 g) and SV-cooked (65.14 mg/100 g) orange samples. SV cooking preserved anthocyanins (855.9 mg/100 g) better than the other methods and was identified as the most suitable method for preserving these compounds, as seen in other anthocyanin-rich foods.

Table 1. *(Continued)* Studies on the effects of the sous vide technique on functional compounds

Reference	*Material*	*Method*	*Results*
Karafyllaki et al., 2023	Horseradish (*Armoracia rusticana*)	This study aimed to demonstrate the effects of different cooking techniques, including boiling, baking, and sous vide, on individual phenolic compounds, Total phenolic content (TPC), Total Flavonoid Content (TFC), color parameters, inhibition of Advanced Glycation End-products (AGE) formation, and antioxidant activity in horseradish. Phenolic acids and flavonoids were analyzed using the HPLC-DAD-MS method. TPC was determined using Folin's phenol reagent. Qualitative and quantitative analyses of polyphenols were performed with a UHPLC system coupled with a diode-array detector (DAD) and mass spectrometry. Antioxidant capacity was determined using the DPPH and ABTS methods, expressed as Trolox Equivalent Antioxidant Capacity.	Fresh and sous-vide samples were characterized by the highest TPC values, while boiled samples exhibited the highest TFC values. The highest antioxidant capacity was observed in fresh horseradish roots. Flavonoids were found at lower concentrations than phenolic acids, with syringic acid identified as the most abundant phenolic compound. After sous-vide processing, horseradish showed greater inhibition of AGE formation. Thermal processing of horseradish roots increased the saturation of yellow and red hues while reducing color brightness.
Colasanto et al., 2023	Italian black rice (*Oryza sativa L.*)	This study investigated the effects of cooking methods on Artemide black rice, comparing innovative sous vide cooking (at 89 and 99 °C) with traditional home cooking methods such as risotto and pilaf. Spectrophotometric analyses were performed on hydroalcoholic extracts to determine free phenolic fractions. Antioxidant activity (AA) was assessed using the DPPH radical scavenging method. Phenolic content (PC) was determined using Folin's phenol reagent. The pH differentiation method was used to measure anthocyanin (AC) and monomeric anthocyanin (MAC) content.	Sous vide at 89 °C was identified as the best method for preserving total polyphenols and antioxidant capacity, while risotto excelled in preserving anthocyanins. No significant differences were observed in protein fractions across cooking methods. In terms of individual compounds, a general decrease in anthocyanin content was observed. Cyanidin-3-O-glucoside, the most abundant anthocyanin in black rice, decreased by 37% and 45% in sous vide 89 °C and risotto samples, respectively, and by 55% and 56% in pilaf and sous vide 99 °C samples, respectively. Free phenolic acids generally increased after cooking, while the fiber-bound fraction remained unchanged across all cooking methods.
Haraf et al., 2024	Beef (*M. semitendinosus*) and kiwifruit (*A. arguta* cv. 'Ananasnaya')	This study aimed to determine the antioxidant activity (AA) and fatty acid (FA) profile of sous-vide beef marinated with 10%, 20%, and 30% kiwifruit pomace in brine and compare it with control samples marinated in brine alone. Changes in the examined parameters were analyzed after 0, 1, 2, and 3 weeks of refrigerated storage. Total polyphenols (TP) in the kiwifruit pomace were determined using the Folin-Ciocalteu method. AA was analyzed for kiwiberry pomace and beef using FRAP and ABTS methods. Total fat content in kiwiberry pomace and beef was tested using the AOAC method.	Adding kiwifruit pomace to marinated beef significantly increased the antioxidant activity (AA) of sous-vide beef compared to control samples marinated only in 3% brine. However, this activity decreased with longer storage times. After one week of storage, samples marinated with 20% and 30% pomace showed the highest FRAP and ABTS values. Sous-vide beef marinated with kiwifruit pomace was characterized by higher PUFA levels, including LA and ALA, in lipids. The beef showed significantly more favorable PUFA/SFA and P/S ratios compared to controls. However, other lipid indices, such as n-6/n-3, AI, TI, and h/H, did not show improvement. One key finding was the high level of palmitic acid (C16:0) in beef lipids when marinated with 30% kiwifruit pomace.

In a study conducted in 2021, the sous vide method was found to positively influence the sensory quality of poultry meat, making it redder, less yellow, and more tender compared to traditional cooking methods. Sensory evaluations indicated that chicken meat cooked sous vide excelled in terms of color, tenderness, juiciness, and overall quality, although its aroma and flavor were less pronounced (Przybylski et al., 2021). These sensory attributes, along with the sous vide method's ability to preserve functional compounds like antioxidants and phenolics, highlight its dual benefits of enhancing both sensory and nutritional qualities of food.

In conclusion, the sous vide cooking method uses much lower temperatures compared to traditional cooking, allowing the production of more nutritious food products with well-preserved bioactive compounds, which are beneficial for health. In future applications, the sous vide cooking technique holds great potential for producing safe foods with enhanced sensory and nutritional properties (Zavadlav et al., 2020).

Sous vide cooking, which is based on the principles of low-temperature and long-duration cooking, may be effective in preserving phenolic compounds and antioxidant capacity.

Czarnowska-Kujawska et al. (2022) demonstrated that the sous vide method effectively preserves phenolic compounds and antioxidant capacity, confirming its role as a gentle thermal processing technique. This aligns with other studies summarized in Table 1. Additionally, Demirel Ozbek et al. (2024) found that sous vide methods lead to the formation of new phenolic compounds, such as protocatechuic acid and p-coumaric acid. These findings indicate that the sous vide method has significant potential not only for preservation but also for the formation of new compounds.

Research suggests that sous vide cooking may enhance antioxidant activity. In the study by Rinaldi et al. (2021), the antioxidant activity of foods cooked using the sous vide method increased after cooking compared to raw products. Similarly, Kosewski et al. (2018) reported that foods cooked sous vide exhibited higher antioxidative potential than those prepared using traditional cooking methods. These findings highlight the advantages of sous vide cooking in preserving nutritional value and enhancing the functional food properties of products. However, a prudent approach is necessary when interpreting results related to increases in bioactive compounds. During bioactive compound analyses, ensuring equal extraction conditions is crucial, as variations in processing methods might enhance extraction quality, potentially leading to misinterpretation of data.

According to Florkiewicz et al. (2019), the sous vide technique is considered the most advantageous method for preserving vitamin C, both immediately after processing and during the storage of processed vegetables. Similarly, the study by Chiavaro et al. (2012) demonstrated that carrots cooked using the sous vide method contained higher amounts of carotenoids, phenolic compounds, and ascorbic acid compared to steamed products, with only a slight reduction in phenolic compounds during sous vide storage. However, the findings of Lafarga et al. (2018) indicated that both steaming and sous vide processing significantly reduced the vitamin C and total phenolic content (TPC) in the studied cruciferous vegetables. These findings suggest that the degree of nutrient retention varies depending on the type of product and the processing conditions applied.

The study by Törős et al. (2024) revealed that mushroom powder cooked sous vide at 70°C exhibited significantly higher β-glucan content compared to the uncooked control sample. This finding suggests that the sous vide technique may enhance the β-glucan content in mushrooms, contributing to their various health benefits.

3. Foaming

Foam is a two-phase gas system dispersed within a liquid phase, formed by whipping or other agitation methods, where gas bubbles are retained within films of differing compositions. The foaming capacity of a solution is influenced by several factors, including surface activity, surface tension at the water-air interface, the film-forming properties of the foaming agent, and the ability to rapidly adsorb at the air-liquid interface. Proteins, due to their amphiphilic properties, play a crucial role in foam formation (Stantiall et al., 2018). Studies on the effects of foaming techniques on functional compounds are presented in Table 2.

Foams are widely used in the food industry for products such as whipped cream, meringues, and mousses. The foam structure provides the desired texture to foods and aims to reduce mass per volume, thereby lowering calorie intake as fewer products are needed per serving. Since air has low viscosity and

Table 2. A Study on the effect of foaming technique on functional compounds

Reference	*Material*	*Method*	*Results*
Zhu et al., 2024	Egg white, potassium bitartrate, garlic juice, and allicin	This study aimed to investigate the effects of garlic juice and allicin (thio-2-propen-1-sulfinic acid S-allyl ester) on the stabilization mechanism of meringues produced from egg whites. Egg whites were whipped with potassium bitartrate, garlic juice, and allicin in separate containers, and their foam conditions were analyzed using microscopy and Gaussian function calculations.	Adding garlic juice to egg white foams increased foam overflow and stability due to the interaction of allicin with free sulfhydryls in egg white proteins during whipping. Allicin also produced firmer foams without altering the pH of egg whites.

surface tension, stabilizers are often used in foam production. Agar plays a vital role in stabilizing the microstructure of foam-based foods and serves as a healthier alternative to high-calorie fat-based foams (Kaur et al., 2022). Additionally, egg white is a commonly used foaming agent due to its high albumin content. It is widely applied in baking and confectionery products to achieve stable foams (Stantiall et al., 2018).

Foams have a structure that traps air within bubbles, similar to an emulsion where one phase encloses another within its structure. Foam structures can be formed by combining different components, such as proteins, water, or oil. The texture of a foam is determined by the size of the bubbles and the amount of liquid within the foam. Some foams are classified as "stiff" foams, which indicates that the structure has solidified (e.g., in bread dough or souffle preparation) (Logsdon, 2018).

In foam production, introducing air or other gases into a product alters its texture and structure, creating a distinct mouthfeel. The foaming technique allows the combination of various flavors without altering the physical properties of the food (Doğan, 2022). This technique is commonly used in foamy desserts, sauces, sweet and sour foams, appetizers, and creamy soups (Batu, 2019). In this method, water contained in solid or liquid foods is transformed into a foam form using natural lecithin and a foaming machine, making it particularly suitable for garnishing dishes, salads, and desserts (Aksoy and Üner, 2016).

Egg white proteins, particularly ovalbumin, ovotransferrin, ovomucin, and lysozyme, contain more air, which is attributed to their higher sulfhydryl group content and lower number of disulfide bonds. This allows for the formation of more intermolecular disulfide bonds during whipping. Studies have shown that the addition of garlic juice or allicin results in firmer egg white foams. The interaction of these components enhances the quality of foaming, leading to more stable and robust foams (Zhu et al., 2024).

Foaming techniques are known for their ability to modify the physical structure of foods, but their impact on functional components has been less explored. Recent studies suggest that incorporating functional ingredients like antioxidants or phenolics into foams can enhance their stability and bioavailability (Zhu et al., 2024). For example, garlic-based foams have shown increased antioxidant retention due to the encapsulating effects of foam structures. Similarly, proteins used as foaming agents can protect sensitive bioactive compounds during storage and processing. Future research should focus on optimizing health benefits by exploring the interaction between foaming agents and functional components.

4. Flavor-Aroma Transfer

The principle behind the flavor-aroma transfer technique is the transfer of the taste, scent, and aroma of natural aromatic foods to other ingredients (Bozbayır, 2021). This technique, which has gained prominence with the molecular gastronomy movement, plays a key role in innovative culinary applications by utilizing the positive effects of highly aromatic foods on other dishes (Bozbayır, 2021; Seçuk & Pekerşen, 2020). Additionally, it contributes to the development of products with new flavor and aroma combinations (Seçuk & Pekerşen, 2020).

Flavor-aroma transfer can be achieved in two ways. The first method involves injecting the aromatic food into the desired dish using a syringe, or cooking the food covered with the aromatic ingredient using the sous vide technique, ensuring the transfer of flavor and aroma (Bozbayır, 2021). For example, injecting pineapple juice into meat before cooking not only imparts an aromatic flavor to the meat but also provides a marinating effect due to its acidic content (Seçuk & Pekerşen, 2020). In the second method, the aroma of the aromatic food is trapped in a siphon and then transferred to the dish (Bozbayır, 2021). Studies on the effects of the flavor-aroma transfer technique on functional compounds are presented in Table 3.

Table 3. A study on the effect of taste-odor transfer technique on functional compounds

Reference	*Material*	*Method*	*Results*
Özdemir et al., 2014	Meatballs and pomegranate peel extract	This study aimed to investigate the effects of pomegranate peel extract (PPE) on the microbial and oxidative stability of cold-stored meatballs. Aqueous extract from pomegranate peel was freeze-dried into a powder and added to meatball formulations at concentrations of 0.1%, 0.2%, and 0.3%.	Adding higher concentrations of PPE to cold-stored meatballs significantly reduced the formation of unpleasant odors. PPE also exhibited antimicrobial effects, extending the spoilage time. The addition of PPE at different concentrations decreased lipid oxidation (TBARs) levels during cold storage. These findings indicate that PPE, rich in phenolic acids, flavonoids, proanthocyanidins, and hydrolyzable tannins, can serve as an antioxidant source in minced meat.

The current body of research directly investigating the effects of flavor-aroma transfer techniques on functional compounds remains limited. Existing studies predominantly focus on the stability, release, and sensory perception of aroma compounds within food matrices rather than their interaction with functional components like phenolics or antioxidants.

5. Smoking

Smoking is defined as the process in which volatile compounds penetrate food products such as fish and meat, either directly or indirectly, as a result of the incomplete combustion of specific woods (Assogba et al., 2019; Pöhlmann et al., 2012). Aromatic wood chips, such as bay, thyme, apple, and cherry, are commonly used in the smoking process. For instance, fish or meat can be subjected to the smoking technique after being cooked using the sous-vide method. Foods intended for serving can be exposed to aromatic wood smoke using a smoke machine and glass cloches just before serving (Özel, 2018). This technique imparts a highly appealing characteristic aroma, color, and flavor to meat products for consumers (Mastanjević et al., 2020).

The smoking process releases phenolic compounds, which are expected to exhibit antimicrobial and antioxidant properties, contributing to the organoleptic characteristics of food (Hitzel et al., 2013). Smoking enhances the sensory qualities of food by providing a distinct color, flavor, and aroma, while also reducing water content and improving preservation due to its bactericidal and antioxidant effects (Škaljac et al., 2018).

Smoking has been a traditional method used since ancient times (Škaljac et al., 2014). Among the functional components of smoke, phenols and acids exhibit the highest antimicrobial activity. While the color imparted by wood smoke is associated with acids and phenols, the reaction-induced color changes in meat during heating are primarily attributed to acids and carbonyl compounds (Toledo, 2007). The color changes in smoked foods result from chemical and physical phenomena occurring during the process. Key phenomena include the polymerization of smoke components (e.g., phenols and aldehydes), the adhesion of smoke coloring compounds, and oxidation reactions between carbonyl groups in the smoke and amino groups in the proteins on the food surface (Marušić Radovčić et al., 2016).

The pyrolysis of cellulose and hemicellulose in wood generates significant amounts of carbonyl compounds that contribute to the brown color on the surface of smoked meats. Meanwhile, the pyrolysis of lignin produces phenolic compounds that act as antimicrobial and antioxidative agents, adding desirable flavors to smoked sausages (Malarut & Vangnai, 2018). These phenolic components not only enhance the aroma of the food but also make the product more flavorful. Smoke also forms a protective film on the surface of smoked products, serving as a barrier against spoilage (Marušić Radovčić et al., 2016).

In traditional Portuguese dry-fermented sausage production, smoking is used to enhance sensory properties such as aroma, flavor, and color. During smoking, components such as phenolic derivatives, carbonyls, and organic acids are transferred to the product, contributing to its characteristic taste and aroma (Roseiro et al., 2011). In northern China, sugar smoking is a more popular method than wood smoking. This technique produces a distinct aroma often associated with caramel notes (Wang et al., 2022).

In industrial smoking processes, smoke production is controlled in industrial oven chambers, and the removal of undesirable compounds is facilitated by positioning smoke generators away from the smoking chambers. In contrast, traditional smoking methods often reach very high combustion temperatures in ovens, where the food is in direct contact with all components of the produced smoke (Škaljac et al., 2014).

Uncontrolled smoking methods can result in the formation of various chemical contaminants, such as polycyclic aromatic hydrocarbons (PAHs), formaldehyde, dioxins, sulfur oxides, nitrogen compounds, and heavy metals (Ledesma et al., 2015). Smoke generated from wood combustion in low-oxygen environments can contain significant amounts of PAHs (Roseiro et al., 2011). These compounds, consisting of two or more fused aromatic rings, are considered potentially genotoxic and carcinogenic to humans (Škaljac et al., 2018).

The composition and concentration of PAHs in smoked meat products depend on several factors, including the type of wood, moisture content, and the temperature associated with smoke production. These factors directly influence the amount of PAHs transferred to the product. Producers must optimize smoking processes to ensure that PAH concentrations remain within the regulatory limits. According to EU regulations, the maximum allowable total PAH concentration in smoked meat products is set at 5.0 μg/kg (Roseiro et al., 2011). Studies on the effects of smoking techniques on functional compounds are presented in Table 4.

Table 4. Studies on the effects of smoking technique on functional compounds

Reference	*Material*	*Analysis*	*Method*	*Results*
Hitzel et al., 2013	Smoked Frankfurter and mini sausages	- PAH analysis: Pressurized liquid extraction (PLE), Gel permeation chromatography (GPC), Solid-phase extraction (SPE), preparation for Gas Chromatography/Mass Spectrometry (GC/MS), and High-resolution Mass Spectrometry (GC/HRMS) analysis. - Phenolic compound analysis: GC/MS using a mass spectrometric detector.	Smoked Frankfurters and mini sausages were analyzed for PAH and phenolic compounds (e.g., guaiacol, 4-methylguaiacol, syringol, eugenol, and trans-isoeugenol) using beechwood chips combined with various spice mixes, including cherry, juniper berries, and bay leaves	Sausages smoked with poplar wood showed slightly higher or lower total contents of the five phenolic compounds compared to beechwood-smoked sausages. However, the use of walnut and poplar wood resulted in a 35-55% reduction in PAH levels compared to the commonly used beechwood.
Marušić Radovčić et al., 2016	Smoked dry-cured ham	Volatile compound analysis: HS-SPME and GC-MS	Biceps femoris samples of dry-cured ham aged for 12–18 months, sourced from nine different producers, were vacuum-sealed and stored at -20°C until analysis. The study aimed to determine the physicochemical, sensory properties, and volatile flavor compounds of the ham.	A total of 87 volatile aroma compounds were identified in smoked dry-cured ham. Samples with higher NaCl content showed lower aldehyde levels, while samples with a longer smoking phase exhibited higher phenol content. Identified chemical groups included aldehydes (35.6%), phenols (34.3%), alcohols (13.8%), terpenes (6.4%), aromatic hydrocarbons (2.6%), alkanes (2.2%), ketones (2.2%), esters (1.7%), and acids (0.7%). Aside from volatile compounds derived from lipolysis and proteolysis, phenols from the smoking process were the second most abundant group, including 4-methylphenol, 3-methylphenol, 2-methoxy-4-methylphenol, 2-methylphenol, 2,6-dimethoxyphenol, and 4-ethyl-2-methoxyphenol.
Petričević et al., 2018	Smoked dry-cured ham	Volatile compounds: Isolated using HS-SPME and analyzed with GC-MS.	The study utilized 24 dry-cured hams produced from the processing of 24 pork legs. The hams were subjected to cold smoking for 20 days and matured for 15–17 months. The aim was to characterize the hams produced using four different processing methods and to analyze volatile compounds.	A total of 149 volatile compounds were identified in dry-cured hams (25 aldehydes, 18 phenols, 12 alcohols, 16 terpenes, 27 aromatic hydrocarbons, 18 aliphatic hydrocarbons, 17 ketones, 9 esters, and 7 acids), with the quantities of 15 compounds determined. Smoked dry-cured hams exhibited higher levels of phenols, aromatic hydrocarbons, and acids, as well as increased levels of terpenes, ketones, alcohols, esters, and aliphatic hydrocarbons, and were characterized by a spiced aroma. Aldehydes were the most abundant volatile compounds in ham samples, representing 34.46–49.78% of the total volatile composition.
Wang et al., 2022	Sugar-Smoked Chicken Drumsticks	Volatile compounds were extracted using solid-phase microextraction (SPME) and identified by GC/MS with reference to the NIST 11 mass spectral database for characteristic ion fragments.	Volatile compounds were extracted using solid-phase microextraction (SPME) and identified by GC/MS. Nine chicken drumsticks from laying hens were smoked at 350 °C and 400 °C with separate additions of sucrose, maltose, fructose, glucose, and xylose as carbohydrate sources. The drumsticks were boiled for 30 minutes in a 1:2 brine solution before smoking. When the cooking pan reached 350 °C or 400 °C, smoking materials were added to the pan. The control group was subjected to the same process without the addition of carbohydrates.	A total of 33 volatile compounds were identified in the sugar-smoked samples. Compared to the control group, the type and content of furans in the sugar-smoked group increased significantly. The pyrolysis of glucose, sucrose, and fructose was found to produce furans in high yields, such as 5-hydroxymethylfurfural (5-HMF) and furfural. The caramel aroma detected in sugar-smoked chicken drumsticks was reported to be associated with 5-HMF. During the smoking process, 5-HMF was pyrolyzed into 5-methylfurfural, and sucrose was identified as an effective carbohydrate source for generating smoke-flavored furans.

Table 4. *(Continued)* Studies on the effects of smoking technique on functional compounds

Reference	*Material*	*Analysis*	*Method*	*Results*
Pino, 2014	Liquid Smoke Flavor Derived from Rice Husk	Volatile compounds were identified using GC/FID and GC/MS.	This study aimed to characterize the volatile compounds in liquid smoke flavor derived from rice husks. A smoke flavor was developed through the pyrolysis of rice husks, selected for their sensory properties. The liquid smoke flavor was prepared by dry distillation of rice husks obtained from a Cuban rice variety.	In the aqueous liquid smoke flavor derived from rice husks, a total of 94 volatile compounds were identified, and their individual quantities were determined. These compounds mainly included carbonyl compounds, phenols, furans, acids, alcohols, esters, and three nitrogen-containing compounds. The liquid smoke flavor obtained from rice husks was found to contain higher amounts of 2-methoxyphenol and its derivatives, making it more similar to smoke derived from softwood species.

The smoking process involves the polymerization of smoke components, generating phenolic compounds that act as antimicrobial and antioxidative agents, contributing to food preservation and flavor enhancement (Marušić Radovčić et al., 2016; Malarut & Vangnai, 2018). Studies have also observed that extended smoking durations result in higher phenol content in foods (Petričević et al., 2018; Wang et al., 2022). However, smoking can also lead to the formation of polycyclic aromatic hydrocarbons (PAHs), contaminants with genotoxic and carcinogenic potential (Ledesma et al., 2015). The concentration of PAHs depends on factors such as the type of wood used, moisture levels, and smoke temperature (Roseiro et al., 2011). Effective measures like controlled smoking durations, appropriate wood selection, and the use of smoke filters can mitigate PAH formation while preserving the desirable qualities imparted by phenolic compounds (Mastanjević et al., 2020).

In a study by Hitzel et al. (2013), the use of walnut and poplar wood for smoke production reduced PAH formation by 35–55% compared to beechwood. To mitigate PAH formation in foods processed with traditional smoking methods, it has been suggested that controlled smoking durations, attention to wood combustion temperatures, proper use of smoke filters, and reduced smoking times are effective measures (Mastanjević et al., 2020).

While the section provides detailed insights into the smoking process and its sensory and preservative effects, the discussion on functional ingredients remains limited. Although phenolic compounds are mentioned for their antimicrobial and antioxidant properties, there is a lack of specific examples or in-depth analysis of how these functional components interact with other compounds during smoking. Moreover, the potential health benefits or stability of these phenolic compounds after the smoking process are not extensively explored.

6. Gelation

Gel is an advanced material characterized by three-dimensional (3D) networks capable of retaining high amounts of water (hydrogel), oil (oleogel), or air (aerogel) due to properties such as high surface area and porosity (Abdullah et al., 2022). In the gelation method, a wide range of textures can be achieved, from soft and elastic to firm and brittle, depending on the nature and concentration of the gelling molecules. These texture variations illustrate that the process of gelation can be simply defined as transforming any fluid into a static solid state. The gelation method requires the rearrangement and ordered binding of molecules to form networks that trap liquids. These networks act as structural frameworks, immobilizing and suspending particles, thus preventing the collapse of the formed structures (Özel & Özkaya, 2016). A century ago, gelatin derived from animal collagen was the primary gelling agent in Western-style cuisines. Today, a variety of gelling agents derived from diverse organisms are routinely used, allowing for precise control of textures and properties in modern culinary regimes. These gelling agents include xanthan gum, methylcellulose, agar, and gellan, each possessing unique biophysical properties. For example, gelatin gels between 4°C and 35°C, while methylcellulose gels between 50°C and 90°C (Brenner & Sörensen, 2015). Emulsion gels, depending on the biopolymer composition of their gel matrix, are categorized into three types: Protein-based emulsion gels (e.g., casein, gelatin, soy, and whey proteins), Polysaccharide-based emulsion gels (e.g., alginate, starch, pectin, and xanthan gum), Mixed emulsion gels (e.g., xanthan gum-guar gum, zein-sodium caseinate-propylene glycol alginate, and soy protein isolate-beet pectin) (Abdullah et al., 2022).

Hydrocolloids are defined as a group of long-chain polymers that disperse easily in water and exhibit complete or partial solubility and swelling tendencies. They can modify the physical properties of solutions through gel formation (via contact with water and microscopic dispersion), thickening, emulsifying, and stabilizing actions. Hydrocolloids can be used to protect bioactive compounds in food and beverages from chemical degradation during storage and to enhance their bioavailability after consumption. As such, food hydrocolloids are versatile natural ingredients essential for formulating next-generation functional food products designed to improve and enhance human health (McClements, 2021). Hydrocolloids can originate from various sources, including plants, animals, algae, and microorganisms. They can also be semi-synthetic, such as cellulose derivatives. Due to their hydrophilic nature, they are also referred to as hydrophilic colloids. While most hydrocolloids possess viscosity-enhancing properties, only a few have the ability to form gels. Gel-forming hydrocolloids include alginate, carrageenan, furcellaran, pectin, agar, gelatin, modified starch, gellan gum, and methylcellulose. The gel-forming property of hydrocolloids is frequently utilized in products like jellies, puddings, and jams (Pirsa & Hafezi, 2023).

Oleogels are innovative structured fat systems that can serve as substitutes for unhealthy lipids and saturated fats (Wang et al., 2024). As an alternative approach, the oleogelation of liquid oils (commonly vegetable oils) has garnered increasing attention. In the food industry, edible oleogels exhibit various solid-like properties and provide beneficial health characteristics, such as reduced levels of saturated and trans fatty acids (Li et al., 2023). Beyond offering solid-like properties without the use of high levels of saturated fats, oleogels can also act as carriers for bioactive compounds (Martins et al., 2018). Oleogels and oleogel-based emulsions derived from different types of vegetable oils are being developed and incorporated into foods such as margarine, yogurt, cakes, and chocolates (Yang et al., 2022).

To process liquid oils, both direct (self-assembly/crystallization of oleogelators and polymeric networks) and indirect (oil absorption and emulsion templates) methods are available. Edible oleogelator molecules can form a three-dimensional network structure, trapping liquid oil to behave like solid fats. To date, various oleogels have been reported, including those made from fatty alcohols, sorbitan monostearate, glycolipids, sodium stearoyl lactylate, and natural waxes (Li et al., 2023). Over the past decade, emulsion gels have emerged as a promising biomaterial for the protection, transport, and improved sensory textures, digestion, bioaccessibility, and bioavailability of health-promoting functional components, enabling the design of healthier formulations (Abdullah et al., 2022).

Studies related to the effects of gelation techniques on functional compounds are summarized in Table 5.

When examining studies utilizing the gelation technique, it has been observed that using carrageenan as a gel matrix (Alejandre et al., 2017; Salcedo-Sandoval et al., 2015) reduces fat content and lipid oxidation in foods. When hydroxypropyl methylcellulose (HPMC) is used as a gel matrix, it significantly lowers saturated fat content (Espert et al., 2021), whereas the use of gellan is effective in preserving probiotics (Picone et al., 2017). Therefore, the gelation technique offers potential health-supporting benefits.

7. Liquid Nitrogen Application

Nitrogen gas, a significant component of the Earth's atmosphere, constitutes approximately 78% of it. Also known as nitrogen gas, it is colorless and odorless. When nitrogen gas is liquefied, it is referred to as liquid nitrogen (Cömert and Çavuş, 2016). The use of liquid nitrogen in food preparation has gained significant popularity in recent years (Božić and Đurović, 2019). Liquid nitrogen is a low-cost, user-friendly, and effective refrigerant. Its extremely low boiling point (-195.8 °C) and high cooling capacity at atmospheric pressure make it a valuable cooling agent.

By rapidly lowering the temperature of food products, liquid nitrogen prevents the formation of large ice crystals that can damage frozen foods (Onurlar, 2023). It is commonly used for grinding plants, which prevents oxidation and thereby preserves the colors and aromas of the plants (Božić and Đurović, 2019).

Liquid nitrogen is also used in ice cream making, offering a distinct advantage in this area. The rapid freezing capability of liquid nitrogen ensures that the crystals formed are extremely small, resulting in an exceptionally creamy and smooth texture for ice cream made with liquid nitrogen. Additionally, when liquid nitrogen is exposed to air, it creates mist, vapor, and an impressive cloud effect, making it a popular element in molecular gastronomy for visual presentations (Batu, 2019).

Table 5. Studies on the effects of gelation techniques on functional compounds

Reference	*Material*	*Phase Types*	*Gel Matrices*	*Aim and Method*	*Results*
Alejandre et al., 2017	Beef patties	Low-energy emulsion gel (3% carrageenan and 1% algal oil)	Carrageenan	The study aimed to achieve an optimized product with maximum hardness and minimum syneresis by combining ingredients. Formulations included a control formulation with pork back fat set at 9% fat content and a modified formulation where pork back fat was entirely replaced with prepared gel emulsions.	Modified patties showed a 70% reduction in fat content compared to the control formulation. The modified patties also demonstrated a 76% reduction in n-6 fatty acids and a 55% increase in long-chain n-3 fatty acids (EPA + DHA). The inclusion of gel emulsions containing reduced n-6 fatty acids and increased long-chain n-3 fatty acids decreased oxidation levels in the modified patties.
Espert et al., 2021	Chocolate	Sunflower oleogel	Hydroxypropyl methylcellulose (HPMC)	The study aimed to investigate the application of sunflower-HPMC-based oleogels as a cocoa butter replacer in chocolate formulations with reduced saturated fat content. Melting, textural, and sensory properties of the chocolates were analyzed. Oleogels were prepared using an emulsion template approach.	Replacing cocoa butter with sunflower-HPMC-based oleogel significantly reduced the hardness of the chocolate. Saturated fat content decreased by 39%. It was suggested that chocolate produced by replacing 50% of cocoa butter with sunflower-HPMC-based oleogel could be a healthier option
Shao et al., 2023	Harbin red sausages	Vegetable oleogels (sunflower, peanut, corn, and flaxseed oils	Ethyl cellulose (EC)	The study investigated the effects of ethyl cellulose concentration and vegetable oil-based oleogels on color, hardness, oil loss, lipid oxidation, and rheological properties. EC concentrations of 6%, 8%, 10%, and 12% were prepared by adding 3g, 4g, 5g, and 6g EC to 50g vegetable oil, respectively. Oil loss in oleogel samples was determined using a centrifuge method. Harbin red sausages were formulated with varying ratios of lean meat and peanut oil-based oleogels (PO10, PO20, PO30, PO40, PO50)	Higher levels of ethyl cellulose resulted in lower oil loss, higher hardness, and increased lipid oxidation in oleogels. Oleogels formulated with peanut oil showed lower oil loss, while flaxseed oil-based oleogels exhibited higher hardness. Corn and peanut oil oleogels led to lower lipid oxidation.
Salcedo-Sandoval et al., 2015	Pork patties	Enhanced fat combination based on konjac gel (olive oil, flaxseed oil, and fish oil)	Carrageenan	The study aimed to evaluate the technological, microbiological, and sensory properties of pork patties by reducing fat content through replacing animal fat with konjac gel and improving the fatty acid profile using a healthier lipid combination stabilized in a konjac gel matrix. Konjac gel was formulated with 64.8% water, konjac flour (5.0%), and i-carrageenan (1.0%), homogenized with 16.2% water and gelatinized corn starch powder (3.0%), cooled to 10°C, and mixed with 10% $Ca(OH)_2$ solution (1.0%).	Replacing pork back fat with varying levels of konjac gel resulted in significant reductions in lipid oxidation. Fat and energy contents were significantly reduced compared to pork-fat-based products (up to 86% and 55%, respectively).

Table 5. *(Continued)* Studies on the effects of gelation techniques on functional compounds

Reference	*Material*	*Phase Types*	*Gel Matrices*	*Aim and Method*	*Results*
Picone et al., 2017	Various emulsion formulations	Emulsion with 40 g/100 g aqueous phase and 60 g/100 g oil phase	Gellan	The study aimed to evaluate the resistance of gelled systems to degradation using in vitro digestion tests and the survival of microorganisms during digestion. Emulsion gel was prepared by homogenizing a gellan solution (0.5 g/100 mL) with an oil phase and storing it. Viability of live L. rhamnosus cells was analyzed in an MRS broth medium containing 1.5 g/100 mL agar.	The gellan gel network served as a barrier against adverse conditions during digestion in the stomach. Gelled solutions containing 0.5 g/100 mL gellan gum were found to be more effective in protecting probiotics compared to non-gelled solutions, with survival rates exceeding 77% in the gel emulsion. Emulsified probiotic cells were protected from bile effects, with viability increasing to 66.35%.
Da Costa et al., 2020	Guava (*Psidium guajava* L.)	Hydrocolloid gel	Agar, low-acyl gellan, high-acyl gellan gum	The study aimed to evaluate the effects of agar and gellan gum on the morphology, texture, and aroma of structured guava. Volatile organic compounds were analyzed using SPME, GC-MS, and SEM.	The volatile profiles of structured guava included aldehydes, alcohols, esters, and terpenes. Processed guava showed a high release of hexanal, (E)-2-hexanal, 1-hexanol, and β-caryophyllene. Guava bars processed with gellan or agar were found to have gastronomic potential.

Another intriguing culinary application of liquid nitrogen arises from the extreme brittleness of frozen materials. Juice sacs from citrus fruits can be prepared by freezing the peeled fruit segments below -130 °C and then breaking them apart using a rigid object. These tiny sacs can be used to enrich ice cream or garnish desserts. Cryogenic grinding of frozen brittle materials produces finer particles and retains more volatile aroma compounds compared to traditional grinding methods, offering an advantage for processing various spices (Aguilera, 2018).

Although liquid nitrogen has no direct adverse effects on consumer health, precautions should be taken, particularly by operators (chefs), to protect their eyes during use. Consumers must also exercise caution. While ingestion of liquid nitrogen is rare, it can cause severe complications, such as gastrointestinal barotrauma (Sivakumaran & Prabodhani, 2018). Another limitation is the need for specialized storage containers (Dewars), which restricts the widespread use of liquid nitrogen in household or restaurant settings. These logistical challenges make liquid nitrogen applications less common outside specialized culinary environments (Caporaso & Formisano, 2016) (Table 6).

Studies examining the effects of the liquid nitrogen technique on foods have shown that this method preserves a significant proportion of nutrients such as polyphenols, pectin, and vitamin C (Cheng et al., 2020) and reduces the activity of polyphenol oxidase, an enzyme responsible for enzymatic browning (Zhu et al., 2020). As a result, this technique not only reduces enzymatic activity in frozen foods but also preserves their functional compounds, offering positive contributions to both sustainability and health.

8. Spherification Technique

Spherification is a widely used technique in the food industry, particularly in molecular gastronomy applications (Onurlar, 2023). This method was introduced to the culinary world in 2003 by Chef Ferran Adrià at the El-Bulli restaurant (Batu, 2019). In modernist cuisine, this technique plays a central role in the creation of faux caviar, eggs, gnocchi, and dumplings (Lee & Rogers, 2012). Broadly, spherification can also be considered an encapsulation method (Caporaso & Formisano, 2016). It involves forming spheres with a thin, hydrocolloid gel-like membrane encapsulating a liquid center. These spheres can be made in various sizes and from a wide range of foods (Hasic, 2021). One of the most notable features of these spheres is their ability to create a flavor burst when gently pressed in the mouth. The sphere should rupture easily, quickly releasing its flavors or contents (Bubin et al., 2019).

Table 6. Studies on the Effects of Liquid Nitrogen Technique on Functional Compounds

Reference	*Material*	*Aim and Method*	*Results*
Cheng et al., 2020	Fresh blueberries (*Chinensis Sonn. Lanfeng*)	The study aimed to investigate the effects of spray liquid nitrogen rapid freezing (NF −20~−100 °C) and gradient thawing on the physical and functional properties of blueberries. Methods such as immersion freezing, refrigeration freezing, microwave thawing, ultrasonic thawing, room temperature thawing, and low-temperature static water thawing were compared.	NF−80 °C freezing combined with −20~−5~4 °C gradient thawing preserved over 95% of polyphenols and other nutritional compounds (including pectin, soluble sugar, and vitamin C) in thawed blueberries. Ultra-low temperature freezing (−100 °C) did not provide significant advantages. Rapid thawing methods like ultrasound and microwave were found unsuitable for blueberries.
Zhu et al., 2020	Wolfberry (*Lycium barbarum* L.)	The study aimed to evaluate the effects of liquid nitrogen spray freezing on water state distribution, color, epidermal microstructure, and the activities of polyphenol oxidase (PPO) and peroxidase (POD). PPO and POD activities were determined using UV spectrophotometry.	NF-100°C freezing offered advantages such as short freezing times and reduced PPO activity. However, NF-80°C was found to provide better sensory quality, similar water distribution to fresh samples, less internal epidermal cell damage, and lower POD activity, making it the optimal freezing method for wolfberry processing.
Castoldi et al., 2017	Rice husks and eucalyptus sawdust	This study utilized liquid nitrogen for the first time as a pre-treatment of plant biomass for enzymatic saccharification. Soluble materials from treated and untreated biomass were analyzed for total soluble phenolics, hydroxymethylfurfural, and furfural using conventional techniques. Endoxylanase and endocellulase activities were measured using 1% carboxymethylcellulose and xylan substrates in a sodium acetate buffer (50 mmol.L^{-1}, pH 5.0) at 50 °C.	Cryogenic milling significantly increased the initial enzymatic hydrolysis rates of eucalyptus wood sawdust and rice husks by more than tenfold without altering the cellulose, hemicellulose, or lignin contents of the biomass. This treatment enhanced the saccharification efficiency of holocellulose without releasing soluble phenolics, furfural, or hydroxymethylfurfural or generating waste

Alginates, natural polysaccharides derived from brown seaweed, are commonly used in the spherification process. These biopolymers dissolve in water, enhancing viscosity and forming gels (Lee & Rogers, 2012). Spherification techniques are classified into two main types based on their preparation method: basic spherification and reverse spherification (TFS). Basic spherification involves injecting a sodium alginate (SA) solution into a calcium bath. This results in calcium ions entering the SA droplet, forming calcium alginate from the surface inward. Conversely, in reverse spherification (TFS), the calcium solution is injected into SA. This causes calcium ions to diffuse from the calcium bath into the surrounding SA, creating an outer layer of calcium alginate (Tsai et al., 2017).

Limitations associated with spherification include selecting the appropriate acidity and calcium concentration, determining the optimal solution density, and adjusting the concentration of flavor compounds (Caporaso & Formisano, 2016). Additionally, even after the spheres are removed from the calcium bath and rinsed, the gelation process of the liquid continues. Thus, it is crucial to serve the spheres promptly to customers (Batu, 2019).

Studies on the effects of the spherification technique on functional compounds are summarized in Table 7.

Encapsulating polyphenols derived from plant extracts within a matrix or membrane in particle form is an effective strategy for preserving their health-promoting properties (Arriola et al., 2016). Encapsulation techniques are typically employed to maintain the stability of bioactive compounds during processing and storage while preventing unwanted interactions with food matrices. This approach not only enhances stability but also facilitates the controlled release of encapsulated compounds (Arriola et al., 2016). Microencapsulation appears to be a promising alternative for improving the absorption of phenolic compounds by epithelial cells (Silva et al., 2021).

The addition of phenolic extracts has been observed to influence the internal structure of edible bubbles, as evidenced by changes in roughness and elemental composition (Bortolini et al., 2024). Research has demonstrated that phenolic compounds can be absorbed onto the inner wall of edible bubbles, altering its roughness. Moreover, these edible bubbles can protect the adsorbed phenolic compounds during simulated gastrointestinal digestion (Bortolini et al., 2024).

Table 7. Studies on the effects of the spherification technique on functional compounds

Reference	*Material*	*Aim and Method*	*Results*
Bortolini et al., 2024	Red berries and edible flowers	The aim of this study was to evaluate the bioaccessibility of phenolic extracts obtained from edible flowers and red berries encapsulated in edible calcium alginate bubbles. DPPH reagent (2,2-Diphenyl-1-picrylhydrazyl) was used for measuring antioxidant activity, and chromatographic analysis was applied to determine the presence of phenolic compounds before and after digestion.	Edible bubbles exhibited up to 182 µg of total phenolic compound concentration (in GAE/g) and antioxidant activity up to 9748.54 µg TE/g as determined by the DPPH test. Simulated gastrointestinal digestion demonstrated preserved antioxidant activity and higher bioaccessibility in edible bubbles compared to isolated extracts. Chromatographic analysis revealed the release of adsorbed compounds during in vitro gastrointestinal digestion.
Arriola et al., 2016	Bertoni (*Stevia rebaudiana*)	This study aimed to encapsulate the aqueous leaf extract of Stevia rebaudiana Bertoni using sodium alginate and evaluate its effects on total phenolic content (TPC) and antioxidant stability. Encapsulation of the optimized extract was performed using extrusion technology. Wet and lyophilized calcium alginate beads were analyzed and compared for TPC and retention efficiency under storage conditions. The TPC of the aqueous leaf extracts of Stevia was determined following a modified Folin-Ciocalteu procedure.	A high correlation was observed between the TPC of the extract and its antioxidant activity, as determined by free radical scavenging and ferric reducing capacity. Lyophilization significantly influenced bead size and morphology, proving to be a suitable technique for preserving encapsulated polyphenols. Both wet and lyophilized beads demonstrated stability in TPC and maintained antioxidant potential during 30 days of storage at 4°C
Silva et al., 2021	Green tea (*Camellia sinensis var. assamica*)	This study aimed to investigate the in vitro simulated gastrointestinal digestion (SGD) and the gastroprotective effect of green tea extract (GTE) microencapsulated with cashew gum and maltodextrin in an ethanol-induced gastric lesion experimental model in mice. The total extractable polyphenol content of the samples was determined using the Folin-Ciocalteu method. The antioxidant capacity of GTE and GTM (green tea microcapsules) was assessed via the scavenging activity of ABTS●+ cation radicals.	The microencapsulation process (GTM) enhanced the bioavailability of polyphenols (28.2%) and antioxidant activity (24.2%) of green tea after in vitro SGD. A dose-dependent gastroprotective effect was confirmed for GTE and GTM, with a concentration of 10 mg/kg effectively preserving gastric mucosa by maintaining glutathione levels in tissues and reducing malondialdehyde levels after alcohol-induced lesions. Overall, GTM demonstrated significant potential for the development of green tea-enriched products and provided a gastroprotective effect beneficial to consumer health.

9. Powdering

The powdering technique involves transforming substances into powder form in an unconventional way by utilizing their chemical and physical properties, rather than traditional grinding methods (Dağlıoğlu, 2019). Using this method, products such as chocolate, hazelnut cream, mayonnaise, olive oil, and bacon can be converted into powder form (Özbek, 2023; Dağlıoğlu, 2019). This technique is applied in two main ways, the first being the transformation of high-fat liquids into fine powders. The process involves adding an additive to the product until it achieves a powder-like consistency, with the feasibility of the technique largely depending on the low density of the additive (Alpaslan et al., 2020). This method is based on mixing high-fat food items with low-density maltodextrin derived from tapioca sugar (tapioca starch) until a powdered form is obtained (Dağlıoğlu, 2019; Aksoy and Sezgi, 2017). These high-fat foods, powdered by mixing with tapioca starch, revert to their liquid form in water-containing environments. One of the most common applications in molecular gastronomy is the powdering of olive oil using maltodextrin (Dağlıoğlu, 2019).

Maltodextrins are primarily formed by the bonding of beta-D-glucose units and are typically classified based on their dextrose equivalent (DE). The DE value determines the reducing capacity of a maltodextrin and is inversely proportional to its average molecular weight. Maltodextrins with different DE values exhibit varying physicochemical properties, such as viscosity, solubility, and freezing point. However, maltodextrins with the same DE value may possess distinct characteristics depending on factors like starch source, hydrolysis procedure, and amylose/amylopectin ratio. Maltodextrins are widely used in food emulsions as stabilizers, sweeteners, and flavor carriers (Guiné et al., 2012).

The second powdering method involves freezing liquid or solid foods by immersing them in liquid nitrogen, followed by breaking them into pieces of the desired size (Alpaslan et al., 2020). In this approach, fluid or non-fluid foods change form when placed in a container filled with liquid nitrogen. The rapid freezing process enhances the brittleness of the food, making it easier to process and break into desired-sized pieces. These granulated products revert to liquid form upon contact with body heat during tasting (Özbek, 2023).

Table 8. Studies on the effects of the powdering technique on functional compounds

Referance	*Material*	*Purpose and Method*	*Results*
Gawałek & Domian, 2020	Aronia berry juice concentrate, tapioca dextrin, maltodextrin	This study aimed to evaluate the efficacy of tapioca dextrin as an alternative carrier to potato maltodextrin in food drying processes. Aronia berry juice concentrate served as the primary research material, with tapioca dextrin used as a carrier and maltodextrin for comparison. The concentrate was spray-dried using a spray dryer, and the resulting powders were analyzed under an electron microscope.	Tapioca starch as a carrier produced powders with superior functional properties compared to potato maltodextrin. Drying speed, temperature, and carrier type significantly influenced powder yield, polyphenol content, and antioxidant capacity. Increased carrier content, higher speeds, and elevated temperatures were found to decrease polyphenol content during the spray drying process of aronia berries.
Moreno et al., 2016	Grape pomace extract, maltodextrin, pea protein isolate, whey protein isolate	This study aimed to compare the effectiveness of natural carriers—maltodextrin, pea protein isolate, and whey protein isolate—in formulating polyphenol-enriched grape pomace extract using spray drying. The outcomes were evaluated based on total phenolic content, flavonoid content, anthocyanin levels, and oxygen radical absorbance capacity.	The drying process indicated that the outlet temperature had a greater impact on particle characteristics than the inlet temperature. When the extract was spray-dried without any carrier material, a 22% reduction in total phenolic content (TPC) was observed. However, even minimal addition of carrier reduced this loss to below 12%. Pea protein and whey protein outperformed maltodextrin in preserving total phenolic and anthocyanin content. Whey protein isolate showed a superior increase in both chemical and cellular antioxidant activities compared to the other carriers.

Studies examining the effects of the powdering technique on functional compounds are summarized in Table 8.

The increasing global consumption of convenience foods has led to a growing demand for dried products, as consumers seek items that facilitate quick and easy meal preparation and storage (Gawałek and Domian, 2020). Spray drying, commonly used in studies, involves optimizing key factors such as feed temperature, inlet air temperature, and outlet air temperature. The feed temperature is related to the viscosity of the liquid and its capacity for homogeneous spraying. The inlet air temperature is directly proportional to the drying rate and final moisture content, while the outlet air temperature serves as an index for controlling the dryer (Moreno et al., 2016).

Drying characteristics and the carrier materials used have been found to influence the properties of the powders. One study indicated that drying speed and temperature significantly affect the nutritional content, emphasizing the importance of selecting appropriate conditions (Gawałek and Domian, 2020). Another study highlighted that the addition of carrier materials reduced the loss of phenolic compounds during the drying process (Moreno et al., 2016).

10. Ultrasonic Applications

"Ultrasound" is typically defined as a form of mechanical energy with frequencies above 20 kHz, beyond the range of human hearing. Ultrasound technology, widely used in the food industry, is a significant and innovative approach with potential applications in gastronomy, including decontamination, marination, tenderization, cutting, diagnostic analysis, homogenization, emulsification, dehydration, rehydration, and molecular gastronomy (Baslar, 2024). In 2010, Sang-Hoon Degeimbre, chef and owner of the renowned restaurant L'air du temps in Noville sur Mehaigne, Belgium, introduced ultrasonic technology to the culinary world as an innovative technique (Onurlar, 2023).

Among the advantages of ultrasonic processing are its chemical- and additive-free nature, its simplicity and speed, and the fact that it does not cause significant chemical alterations in food (Caporaso & Formisano, 2016). Considering these benefits, this technique holds great potential for producing high-quality, functional, and unique food products in the future. Furthermore, the combination of heat and pressure in industrial applications could lead to the broader adoption of microbial and enzymatic inactivation processes (Türksönmez & Diler, 2021). For instance, high-

Table 9. Studies on the effects of ultrasonic applications in molecular gastronomy

Reference	*Material*	*Purpose and Method*	*Results*
Chang and Chen, 2002.	Wine made from rice and corn	The study aimed to investigate whether aging with 20 kHz ultrasonic waves has the potential to produce a wine comparable in quality to traditionally aged wine.	The pH value of rice wine treated with 20 kHz ultrasonic waves slightly increased as the number of treatments increased, resulting in a less sour taste and making the ultrasonically aged wine more favorable. In contrast, the pH value of corn wine treated with 20 kHz ultrasonic waves remained the same as that of untreated corn wine despite multiple treatments. It was observed that the alcohol loss in ultrasonically aged corn wine was slightly lower than that in rice wine. While rapid aging was achieved in rice wine, proper aging could not be accomplished in corn wine.
Doguer et al., 2021	Purple basil (*Ocimum basilicum* L.)	This study aimed to investigate the potential anticancer activities of sirkencubin syrup enriched with purple basil on human colon carcinoma cells (Caco-2). Additionally, the effects of ultrasonic treatment on purple basil components and bioactive compounds were explored in terms of changes in total phenolic, flavonoid, ascorbic acid, and total antioxidant content using modeling and optimization methods.	Ultrasonic treatment (UT) was found to enhance the antioxidant activity and increase the levels of bioactive flavonoid and phenolic compounds in sirkencubin syrup enriched with purple basil. The ultrasonic treatment of purple basil syrup (PBS) samples reduced the total amount of ketones by 45.5%. Moreover, it was observed that the ester aroma compounds in PBS were 0.19 µg/kg lower than in UT-treated PBS samples. The aroma and sensory properties of UT-PBS were found to be more acceptable compared to other beverages, marking an important observation.
Yıkmış et al., 2022	Purple onion (*Allium cepa*)	This study evaluated antihypertensive, anticancer, antidiabetic, antimicrobial properties, volatile profiles, phenolic compounds, organic acids, minerals, and sugar components for untreated purple onion vinegar (U-POV), thermally pasteurized purple onion vinegar (P-POV), and ultrasound-enriched purple onion vinegar (UT-POV) samples. Total phenolic content (TPC) was analyzed using the Folin-Ciocalteu method, antioxidant activities were assessed through the DPPH radical scavenging assay, and the total antioxidant capacity was determined using the CUPRAC assay. Flavonoid content was measured via aluminum chloride colorimetric analysis	Ultrasonically treated purple onion vinegar (UT-POV) demonstrated enhanced antidiabetic and antihypertensive effects. The ultrasound process increased the amounts of polyphenols, including catechin, gallic acid, hydroxybenzoic acid, and protocatechuic acid. Additionally, UT-POV samples were enriched with potassium (K) and zinc (Zn) minerals. Compared to thermally pasteurized purple onion vinegar (P-POV), UT-POV had a lesser impact on volatile compounds. Ultrasonically processed purple onion vinegar is considered a promising option for sustainable gastronomy
Dahroud et al., 2016	*Lactobacillus casei subsp.casei* ATTC 39392	This study aimed to evaluate the effects of low-intensity ultrasound technology on improving metabolic activity for the production of L-lactic acid by Lactobacillus casei in different media (MRS broth)	Enhanced fermentation was observed, with increases in lactic acid production, cell proliferation, and substrate consumption. No adverse effects on cell morphology were detected.

intensity ultrasound can be a preferred method for preserving milk and dairy products due to its ability to deactivate pathogenic microorganisms and enzymes. Additionally, it can induce physical-chemical changes in food, positively influencing probiotic viability and metabolic activity (Guimarães JT et al., 2019). Table 9 provides an overview of a study examining the effects of ultrasonic applications on molecular gastronomy.

Various studies employing ultrasonic applications have demonstrated positive effects of ultrasonic waves in accelerating wine aging (Chang and Chen, 2002) and enhancing fermentation processes (Dahroud et al., 2016). Ultrasonic treatment applied to purple onion vinegar has been observed to increase the levels of polyphenols such as catechin, gallic acid, hydroxybenzoic acid, and protocatechuic acid (Yıkmış et al., 2022). Evaluating these studies reveals that ultrasonic applications hold significant importance in terms of health and sustainability.

Conclusion and Recommendations

Molecular cooking techniques offer innovative alternatives that significantly influence the functional components of foods, providing benefits in both nutrition and safety. Methods such as low-temperature cooking, vacuum processing, and smoking can enhance antioxidant capacity and bioavailability while preserving essential nutrients like vitamins and polyphenols. These techniques also help prevent the formation of harmful compounds, such as acrylamides and heterocyclic amines, which are commonly associated with high-temperature cooking processes. Furthermore, molecular cooking contributes to food safety by reducing pathogenic microorganisms without compromising sensory quality.

To advance this field, the effects of molecular cooking techniques on functional components across various food systems must be further investigated. Standardizing cooking parameters is necessary to ensure consistent health benefits. The food industry can leverage these techniques to create healthier, safer, and more sustainable food products that align with the increasing demand for functional and nutrient-rich foods.

Molecular cooking techniques play a vital role in promoting sustainability through energy efficiency. Methods such as low-temperature cooking and vacuum processing can reduce energy consumption, thereby minimizing environmental impact. Controlled processing environments help optimize water usage and reduce food waste, contributing to a more sustainable food production system. From a practical standpoint, molecular gastronomy enables the creation of innovative food products with nutritional richness and diverse flavor profiles, offering consumers healthier and more enjoyable options.

Recommendations for the Implementation of Molecular Cooking Techniques:

1. Raising Awareness and Education: Educating food scientists, chefs, and consumers about molecular cooking techniques can help build a broader knowledge base, highlighting their advantages and proper application methods.
2. Improving Equipment Accessibility: Developing molecular cooking equipment that is more affordable and accessible can facilitate the widespread adoption of these techniques.
3. Establishing Health and Safety Standards: Creating and enforcing clear health and safety standards for molecular cooking techniques is essential to ensure the safe processing and consumption of foods.
4. Developing Innovative Food Products: Leveraging the advantages of molecular cooking techniques can lead to the creation of new food products that offer high nutritional value and unique flavor experiences.
5. Integrating Molecular Techniques into the Agri-Food Chain: Applying molecular cooking techniques throughout the farm-to-table process can reduce food waste and ensure the delivery of fresh, nutritious foods to consumers.
6. Conducting Comparative Studies: Further research is needed to evaluate the effects of molecular cooking techniques on food components in comparison to traditional methods, as well as their environmental impacts.

In conclusion, molecular cooking techniques contribute to the production of foods that are both nutritionally rich and flavorful, enhancing consumer health and satisfaction. These techniques hold significant potential in advancing health, sustainability, and future applications. Their broader adoption and further development can open pathways to a more sustainable and innovative future for the food industry. However, ongoing in-depth studies are required to thoroughly understand their effects on the chemical stability and nutritional value of functional compounds, ensuring their optimal use in food production systems.

Declaration of Competing Interest

The authors declare that they have no financial or non-financial competing interests.

Author's Contributions

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