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Reformulation and Characterization of Mediterranean Ingredients by Novel Technologies

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Abstract
The Mediterranean diet is known for its health benefits, mainly due to its diverse ingredients, such as fruits, vegetables, grains, nuts, legumes, and olive oil. This review examines the reformulation and characterization of these Mediterranean ingredients using several novel food processing and analytical technologies. Reformulation technologies discussed include microwave pasteurization, microwave vacuum drying (VMD), pulsed electric field (PEF), high-pressure homogenization (HPH), freeze drying, high hydrostatic pressure (HHP), and cold plasma technology (CP). Characterization technologies covered include Nuclear Magnetic Resonance (NMR), Electron Paramagnetic Resonance (EPR), and Near Infrared (NIR) spectroscopy. Nonthermal techniques such as PEF, HHP and CP are particularly noteworthy for their ability to preserve nutritional and sensory qualities without using high temperatures, that can degrade sensitive compounds. The main requirement for these processing methods is to ensure that the food retains its beneficial nutrients and natural flavors while extending its shelf life. Analytical techniques like NMR, EPR, and NIR spectroscopy provide detailed insights into the molecular composition and quality of food products. These techniques allow for precise optimization of processing methods, ensuring the best possible quality and nutritional value. The integration of these advanced processing and analytical techniques with traditional Mediterranean ingredients offers significant advancements in food science, improving food quality, nutritional value, and the sustainability of food production. This review aims to provide a comprehensive understanding of how these novel technologies can be applied to optimize the nutritional and sensory qualities of Mediterranean ingredients while enhancing their health-promoting capabilities.

Keywords Mediterranean diet · Food reformulation · Nonthermal processing · Novel food processing technologies

Introduction

The Mediterranean diet, often abbreviated as MedDiet, is based on the traditional eating habits of countries bordering the Mediterranean Sea, including Türkiye, Greece, Italy, Croatia, Spain, Lebanon, and others, and is widely accepted worldwide as a healthy lifestyle model [1]. The diet is based on the consumption of healthy oils such as olive oil, whole grains, fruits, vegetables, legumes, nuts, seeds and fish [2]. Among the basic elements of the Mediterranean diet, tomatoes are an indispensable component of the diet. Tomatoes are a vegetable that forms the basis of Mediterranean diet and are extremely rich in powerful antioxidants such as lycopene which is a carotenoid that protects cells from the damage of free radicals and protects against chronic diseases [3]. When used with tomatoes, olive oil increases the bioavailability of lycopene, making it more effective in the body [4]. In addition, fruits and vegetables provide essential vitamins, minerals, and fiber, while whole grains contribute to carbohydrates and additional fiber [5]. Consuming plenty of fresh vegetables and fruits increases the antioxidant capacity of the diet, reduces oxidative stress caused by free radicals in the body and minimizes the risk of developing chronic diseases [6]. Moreover, legumes and nuts offer plant-based protein and healthy fats. Olive oil, a staple in the Mediterranean lifestyle, is a significant source of monounsaturated fatty

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acids with health-promoting properties. Fish, particularly oily varieties like salmon, sardines, and mackerel, are important for their omega-3 fatty acids [2]. Fish and seafood, on the other hand, reduce inflammation and protect against cardiovascular diseases as a source of omega-3 fatty acids. This view of diet and lifestyle is associated with numerous health benefits, including a lower risk of heart disease, stroke, type 2 diabetes, and certain cancers, in addition to improved life quality [7, 8]. Numerous studies have searched for a link between MedDiet and diseases. Some recent studies have revealed that the Mediterranean diet offers long-term protection against cardiovascular diseases [9, 10]. Some other studies have shown that MedDiet helps with diabetes and obesity by improving insulin resistance and enabling better glycemic control [11–13].

While the Mediterranean diet is known as a healthy lifestyle model, the changing living conditions and consumption habits of modern society require the reformulation of traditional products belonging to this diet. Innovative food processing technologies ensure that the nutritional values of these traditional products are preserved, the bioavailability of their bioactive components is increased and they are made more suitable for consumer demands. In particular, the processing of basic products such as tomatoes requires technological innovations to ensure higher bioavailability of lycopene. For example, technologies such as pulsed electric field, high-pressure homogenization and freeze-drying extend the shelf life of tomatoes and other foods, minimize nutrient loss and improve sensory properties such as flavor and texture [14]. The implementation of such technological innovations is of great importance for the sustainability of the Mediterranean diet and its accessibility to the masses in the modern age. Mediterranean diet products reformulated with new technologies both preserve the positive effects of traditional foods on health and meet consumer expectations. Therefore, the reformulation of Mediterranean diet products is a great scientific and industrial necessity in the field of health and nutrition. Reformulation and characterization of food ingredients could be performed by several novel food processing and analytical technologies. Reformulation techniques include *microwave pasteurization*, which uses microwave energy to ensure food safety and maintain nutritional and sensory qualities; *microwave vacuum drying*, which combines microwave energy with a vacuum to efficiently reduce moisture content while preserving nutrients and sensory attributes; *pulsed electric field* (PEF), which uses short bursts of high voltage electricity to permeabilize cell membranes, enhancing the extraction of bioactive compounds and extending shelf life without significant thermal damage; *high-pressure homogenization* (HPH), which applies high pressure to disrupt cellular structures, improving the extraction of valuable compounds and enhancing the stability and properties of food products; freeze drying, which removes water from frozen food through sublimation, resulting in high-quality dried products that retain their nutritional and sensory properties; *high hydrostatic pressure* (HHP), which subjects food to high pressure to inactivate microorganisms and enzymes, preserving nutritional and sensory qualities while extending shelf life; and *cold plasma technology*, a non-thermal method that uses ionized gas to inactivate microorganisms and enzymes on food surfaces, maintaining nutritional and sensory properties without the need for high temperatures. Characterization technologies would include *Nuclear Magnetic Resonance* (NMR), which provides detailed insights into the molecular composition and structure of ingredients*; Electron Paramagnetic Resonance* (EPR), which is used to detect and quantify free radicals and other paramagnetic species and provide information on the oxidative stability and quality of food products; and *Near Infrared (NIR) spectroscopy*, which offers a rapid and non-destructive analyses of the composition and quality of ingredients, including moisture, protein, fat, and carbohydrate content.

The FunTomP project, funded under the PRIMA program in 2021, brought together 16 partners from 9 different countries to collaboratively develop innovative solutions for the valorization of tomato processing by-products. The project focused on extracting and utilizing functional ingredients such as fibers, proteins, and bioactive compounds, aiming to reduce waste and enhance sustainability in the agro-industrial sector.

In this review, we also highlight the processing techniques and characterization methods employed during the project, showcasing the technological advancements and interdisciplinary approaches that contributed to achieving its objectives.

Today, the MedDiet is valued for its nutritional value and its role in promoting health and preventing disease, making it a valuable model for healthy eating worldwide. This review therefore aims to provide an insight into how new technologies are being used to reformulate and characterize Mediterranean ingredients. Moreover, this review challenges how innovative food processing technologies and analytical tools can optimize the nutritional and sensory qualities of Mediterranean ingredients especially tomato and olive while enchancing their health-promoting capabilities.

Reformulation of Mediterranean Ingredients by Novel Technologies

Microwave Pasteurization

Microwave pasteurization represents a thermal food processing technique that employs microwaves to ensure food safety, maintain nutritional and sensory qualities, and extend the shelf life of food. This method involves interacting food components with microwave energy to facilitate pasteurization. There are two main mechanisms through which microwave heating occurs. Firstly, microwaves induce a dipolar rotation of the water molecules at the frequency of the waves in the presence of an alternating electric field. This molecular motion generates frictional heat [15]. Secondly, the microwaves cause polarization of the ions, whose movement also contributes to heat generation [15]. For microwave pasteurization the heat is not transferred via a hot medium but is generated inside the product. The inactivation of microorganisms and enzymes primarily results from this thermal effect [16]. Despite the predominance of thermal mechanisms, some scientists suggest that non-thermal effects, such as the destabilization of proteins and cell membranes by the electromagnetic field, may also play a role in microbial inactivation. However, this remains a subject of ongoing debate [17].

Due to its unique advantages and challenges, microwave pasteurization has attracted significant attention from researchers and the food industry. Unlike conventional methods that rely on conduction or convection and use hot water or steam, microwave pasteurization employs a volumetric heating approach, where heat is generated throughout the material simultaneously. This method is known for its shorter process times and reduced energy consumption, with an estimated energy efficiency of around 30%, compared to 13–29% for conventional methods [18]. The rapid heating and reduced processing time contribute to minimal impact on food quality and preserve its sensory and nutritional properties [19].

However, microwave pasteurization also presents certain downsides. The nature of the electromagnetic field can lead to an uneven energy distribution, resulting in hot and cold spots within the product. Cold spots may lead to inadequate pasteurization, while hot spots may cause burning or overprocessing of the product. Therefore, researchers have focused on design improvements to overcome these problems and produce reliable equipment at pilot and industrial scale [20].

Numerous studies have investigated microwave pasteurization as a promising method to replace conventional methods. The appropriateness of pasteurization, process efficiency, and the sensory and nutritional properties of the products are compared with conventional methods. This review focuses on Mediterranean ingredients like tomato products, olives, and legumes. It highlights the potential benefits and limitations of preserving the integrity and quality of these foods. Arjmandi et al. [21] utilized a semi-industrial continuous microwave system under high power/short time and low power/long time conditions and compared it to a conventional method (96 °C, 35 s holding time) for pasteurizing tomato puree [21]. It was found that the total antioxidant capacity (by ferric reducing antioxidant capacity) and vitamin C content were higher in the microwave-treated sample than in the conventionally processed samples. Particularly, the process with high power/short time (1900–3150 W, 150–180 s) resulted in enhanced viscosity, increased lycopene content, and a lower residual enzyme activity.

Pérez-Tejeda et al. [22] compared microwave (2.67 min at full power operation with 3 min holding time) and conventional pasteurization (heat treatment at 93.3 °C for 26.5 min proposed by FAO) on physical properties of tomato puree and microbial inactivation kinetics by calculating lethality ($F_{93.3}^{8.9}$) and intentional inoculation with *Escherichia coli* [22]. It was found that flavor, color, and overall acceptability scores did not differ significantly between microwave and conventional pasteurization. A 5-log reduction in the *E. coli* population was observed after microwave pasteurization. They showed deviation in come-up time (2.67 min, 26.5 min) and total process time (5.67 min, 53 min), while similar maximum temperature (88.2 °C, 87.5 °C) and lethality values (1.11 min, 1.10 min) were obtained for microwave and conventional treatments, respectively. Stratakos et al. [23] studied the pasteurization of tomato juice in an industrial-scale microwave pasteurizer and examined its physical, chemical, and microbial properties during storage [23]. The work concluded that microwave-pasteurized juice was like the conventional one regarding physicochemical and microbiological characteristics, achieving the desired microbial reduction. The microwave-pasteurized juice had higher initial antioxidant activity (measured by the ABTS method) and showed a better cytoprotective effect. Besides using microwaves for microbial inactivation, microwave processing can improve product quality and stability and increase functionality. Farag et al. [24] found that microwave treatment of olive fruits (3 to 12 min) significantly reduced lipase activity and thus increased the stability of olive oil during storage [24]. There were no significant differences in the chemical composition of olives after microwave treatment. Mahalaxmi et al. [25] showed that proteins in lentil flour can be modified by microwave treatment to obtain better water and oil absorption capacity and emulsifying properties [25]. The lentils were subjected to different combinations of power (540 to 900 W) and time (2 to 6 min). The enhancement of techno-functional properties was mainly attributed to the denaturation of the proteins, i.e., changes in the secondary structure.

Microwave Vacuum Drying (VMD)

Drying has been one of the major mass transfer processes in food technology [26–28]. Different drying systems and operation types, such as convection, conduction, radiation, and combinations, have been developed for the food industry. Drying is not only used to preserve food but also to cook it. However, the conventional drying process, which is time-consuming and energy-inefficient, does not preserve product quality adequately as nutrients, such as color, flavor, and texture, are lost. This negatively affects the sensorial properties of the food.

Microwave Vacuum Drying (VMD) technology is already superior to conventional techniques regarding moisture reduction in food due to its fast and efficient drying. This technique is based on the microwaves' absorption by the water molecules in the food matrix, which causes vibrations and movement of the water molecules, generating heat. This reaction is promoted by the polar ions in the food matrices. There are some parameters affecting the efficiency of the drying process, such as vacuum pressure (kPa), frequency (Hz), microwave power (kW), temperature (°C), composition, and dielectric properties of the food [29]. Vacuuming helps to lower the water's boiling point by reducing the pressure in the microwave chamber, which enables efficient drying. This preserves bioactive nutrients and maintains the sensory attributes of the food. Moreover, this microwave vacuum drying system helps to significantly reduce the drying time compared to conventional hot air drying and freeze-drying. Microwave vacuum drying is more effective than hot air drying in terms of energy consumption as this system consumes less energy per kilogram of evaporated water than conventional drying. For example, research on microwave vacuum drying (VMD) of kiwifruit compared to freeze drying (FD) and air drying (AD) has shown that the energy savings with VMD are 96.18% and 95.42%, compared to FD and AD, respectively [27].

This technique has been very popular in the food industry, especially for food containing considerable amounts of heat-sensitive compounds, such as fruits, vegetables, and meat [30–35]. The nutritional value of the food can be preserved more in VMD systems than in conventional hot air drying, as the long time and long temperature drying process lead to the degradation of many functional components, for example, phenolics [36]. However, there may be some exceptional cases. Gül et al. [36] stated that conventional drying resulted in higher lycopene content than VMD in tomatoes, as the release of lycopene is promoted at higher temperatures and longer processing times [36]. Another study on the drying of “Deveci” pear has suggested that a vacuum-assisted microwave system has provided higher protein content, rehydration ratio, and mineral content with increasing vacuumization [37]. In addition, energy consumption was reduced while the drying rate was increased at higher vacuum levels. The microstructure of the fruit was also affected by VMD applications. The pore size and its distribution increase with VMD applications. A lower oxygen concentration in the vacuum chamber causes less oxidation of polyphenols in food [38].

Moreover, browning reactions in the food can be inhibited by VMD, so the color is improved. Another study pointed out that VMD reduces the degradation of quercetin derivatives in apple slices compared to hot air drying [26]. In addition to substantial health benefits, VMD systems can achieve better environmental sustainability and reduce greenhouse gas emissions [39]. The VMD system has been utilized to reformulate Mediterranean food products [36], and it was found that a functionalized tomato snack bar can be produced using this methodology. This drying type has reduced processing time and energy consumption while maintaining the physicochemical properties and preservation of bioactive compounds such as lycopene in tomatoes.

Since consumers become more aware of the importance of a healthy Mediterranean diet, there has been considerable growth in the popularity of microwave vacuum applications for those foods. For example, apples, strawberries, mangoes, carrots, potatoes, tomatoes, mushrooms, and raisins are dried utilizing this method [28, 40–44]. The foods can have higher quality, lower processed, better nutritional value, reduced risk of certain diseases, longer shelf life, cost-effective processing, and improved palatability as opposed to air drying. These are the main benefits of this technology [45]. Vitamins, minerals, and fiber are essential dietary nutrients in Mediterranean foods. Therefore, the freshness of the food should be maintained by dehydration to preserve it during the processing of fruits and vegetables. The excellent quality of dried banana slices was achieved by checking the sensorial properties [46]. Lower density, better rehydration potential, and more color retention were achieved in dried carrot slices by microwave vacuum drying compared to traditional air drying [28]. Also, the overall preference for the sensory properties of these carrots was rated better than that of freeze-dried ones. The unique puffed structure of the carrot slices after microwaving was considered a preferred property, especially for the reformulation of Mediterranean-based snack-type products [43]. Smaller alpha-carotene content loss was achieved by VMD as opposed to air drying due to rapid processing [47]. Vitamin C was also retained better in VMD. Honey drying was completed without darkening by using VMD [41]. Although many research and development endeavors exist for microwave applications in reformulating Mediterranean-based food, vacuum-assisted microwave applications must be evaluated in further studies [48].

High-intensity Ultrasound

High-intensity ultrasound is the non-thermal method of food processing whose mechanism is based on mechanical ultrasonic waves that generate vibrations in the medium. The ultrasonic generator produces an alternating electrical current at the required ultrasound frequency, while the ultrasonic transducer, which is usually piezoelectric, converts the electrical pulses into sound energy. The resulting mechanical vibrations are amplified in the amplifier and the ultrasonic waves are emitted into the target medium. Taking into account the intensity and frequency of the ultrasonic waves and the field of application, ultrasound is divided into low-intensity ultrasound (less than 1 W/cm^2) with high-frequency waves (above 100 kHz) and high-intensity ultrasound (from 10 to 1000 W/cm^2) with low-frequency waves (from 20 to 100 kHz) [49]. Low-intensity ultrasound is most commonly used in the food industry to analyze the physico-chemical properties of food, while high-intensity ultrasound is used in various food processing procedures, with emphasis on the inactivation of microorganisms [50, 51].

In food processing, ultrasound has physical and chemical effects on the treated raw materials. The chemical effect of ultrasound is attributed to the formation of free radicals H + and OH-, which result from the decomposition of water molecules within the oscillating bubbles. In contrast, the physical effects are numerous and complex and are based on transient acoustic cavitation with numerous associated phenomena, rapidly changing mechanical loads and sometimes cellular resonance [52].

The primary mechanism of ultrasound is based on transient acoustic cavitation and the formation of thousands of bubbles caused by the propagation of ultrasonic waves in a liquid medium [50]. The action of the ultrasound on the liquid leads to alternating cycles of compression and expansion of the molecules, which changes the distance between them. If the distance between the molecules is large enough, cavities are created and the bubbles grow until they reach a critical size. When the critical size is reached, the bubbles collapse abruptly, creating micro-regions with extremely high temperatures (from 4500 to 5000 K), pressures (over 100 MPa) and shock waves [53].

The increase in temperature and pressure, the formation of free radicals and their recombination with other molecules as well as the decomposition of macromolecules are part of the mechanism of microbial inactivation supported by ultrasound. The transient acoustic cavitation causes the collapse of the microorganism's cell wall and the release of cytoplasmic contents from the cell. In addition to the aforementioned destruction, coagulation of the cell proteins also occurs, which consequently contributes to the lethal effect of ultrasound treatment on microorganisms, i.e. cell death [50]. The success of inactivation largely depends on the applied amplitude, treatment time, power, temperature, sample volume, food properties, but also on the characteristics of the microorganism [52]. One of the many positive studies is the study on tomato juice, where the inhibitory effect of ultrasound on microorganisms was observed without significant effects on the nutritional and sensory properties of the tomato product [54]. Compared to conventional thermal methods, ultrasound ensures the microbiological safety of the product at significantly lower temperatures and shorter treatment time (energy more efficient) [52, 55]. This makes ultrasound a more cost-effective and sustainable alternative to conventional methods. During storage, however, there is the possibility of recovery of damaged cells. A solution for this could be a barrier technique that combines ultrasound with other non-thermal food processing techniques or methods such as pH reduction. This approach can slow down the growth of microorganisms or cause their death. If recovery is successfully prevented, the microbial cells can no longer grow and a higher degree of inactivation and better microbiological stability of the product can be achieved [56].

In addition to the positive effects on microbiological safety, the processing of fruit juices with ultrasound enables better preservation of the nutritionally valuable ingredients, the sensory properties and the general quality of the final product compared to conventional thermal treatments. In addition, the antioxidant activity of fruit juices can be increased, which consequently affects the better stability of the product during storage time. Furthermore, ultrasound is widely used in the food industry for meat processing and mass transfer processes of fruits and vegetables [52]. Despite the many benefits, ultrasonic treatment can cause the degradation of lipids, changes in the color and viscosity of the product, as well as the formation of atypical aromas and free radicals [52], so widespread application should be approached with caution.

Ultraviolet-C (UV-C) Light

UV-C light is a part of the electromagnetic spectrum with wavelengths ranging from 200 to 280 nm. This non-thermal technology has been granted approval by the US Food and Drug Administration (FDA) for the treatment of juices and solid foods (e.g. minimally processed or ready-to-eat fruits and vegetables) [57], and by the European Food Safety Authority (EFSA) for treating milk (for the enhancement of vitamin D content and shelf-life extension) [58] and bread for shelf-life extension [59]. These approvals make UV-C a compelling choice for manufacturers looking to improve product quality and extend shelf-life. UV-C is also used for the decontamination of food contact surfaces, air, and water [60]. The food industry finds this treatment appealing because of its antimicrobial effectiveness and minimal impact on physicochemical and sensory properties when used at proper doses [57, 61].

Also, UV-C doesn't produce any potentially hazardous chemical residues, has a low cost and a low carbon footprint, and can prevent cross-contamination because it can be applied after packaging [62–64]. In addition, the utilization of UV-C stands out as a highly effective non-thermal technology for microbial inactivation in low-water activity powdered foods, such as semolina and flour that is largely used in the production of pasta in Mediterranean countries like Italy [65, 66].

UV-C radiation has been proven to be effective for inactivating a wide range of microorganisms, such as bacteria (including endospores), viruses, yeast, molds, and parasites. Microbial inactivation is achieved through the absorption of UV-C radiation by the DNA/RNA and proteins of these organisms, leading to structural damage through photo-oxidation and ultimately rendering them inactive or non-viable [59]. The wavelength range of 250 nm to 270 nm has been demonstrated to yield optimal germicidal efficacy, as this is the range where maximal absorption by nucleic acids is achieved [67, 68]. UV-C-induced damage in DNA and RNA is caused by the dimerization of pyrimidine molecules which leads to the formation of pyrimidine dimers that impede the processes of transcription and replication of nucleic acids, resulting in genetic mutations and cellular death [67]. UV-C absorption by amino acids inhibits enzymatic activity and reduces the functionality of proteins [69]. DNA photoproducts formed after UV-C absorption include cyclobutane pyrimidine dimers and pyrimidine 6–4 pyrimidone photoproduct [70]. It is observed that cyclobutane pyrimidine dimers that are formed between adjacent thymine bases [71] are the predominant and most cytotoxic lesions after UV-C irradiation. However, the 6–4 pyrimidine-pyrimidone photoproducts possess more severe and potentially fatal mutagenic consequences [72].

Several key factors play a role in the efficiency of UV-C light for decontamination purposes. These factors include the dosage of UV-C light applied (this is influenced by factors such as the type of lamps used), the duration of exposure, the equipment configuration, and the optical properties of the matrix to be treated. Additionally, the effectiveness of UV-C light can vary depending on the type of microorganism being targeted. For example, Gram-positive bacteria typically are more resistant than Gram-negative bacteria due to their thicker peptidoglycan layer which may impede the penetration of UV light [73]. Higher UV-C doses cause severe alterations in microorganisms, making their reactivation non-viable but when UV-C is used at lower doses, microorganisms have the ability to survive [74–76] because they can undergo dark-repair or photo-repair (photoreactivation) mechanisms to repair damage caused by UV-C exposure [77, 78]. Additionally, the presence of organic matter, color compounds, or suspended particles in food (liquid foods in particular) can absorb UV-C rays or block their transmission [79]. A high amount of both organic and inorganic particles in the product to be treated decreases UV transmittance (a measure of the level of radiation absorbance) and hinders the ability of UV-C photons to effectively penetrate the product, ultimately limiting their ability to deactivate microorganisms [78]. Thus, it is crucial for food processors to consider all of these factors when utilizing UV-C light for preservation purposes, and to have a thorough understanding of the scientific principles behind this technology to maximize its effectiveness. To overcome these issues and improve food quality, UV-C has been applied in conjunction with other preservation methods such as refrigeration, ozonated water (10 ppm) activated with UV-light, disinfection/antimicrobial solutions, ultrasound, microwave, high-pressure processing, and mild heat treatments [58, 79].

Besides the demonstrated efficiency of UV-C in microbiological inactivation, previous studies have shown that UV-C irradiation can increase the availability of phytochemicals in a variety of foods and beverages. Following UV-C treatment, certain studies have shown elevated carbohydrate content as well as preserved or even increased phenolic content and antioxidant activity [80]. UV-C increased the levels of total phenolic content, flavonoid content, and antioxidant activity of tomato, broccoli, amaranth, and red cabbage [81].

Despite these advantages, UV-C treatment can cause the degradation of health-promoting bioactive compounds in food. Exposure to high doses and/or long exposure time to UV-C radiation can lead to oxidative stress, which in turn can damage cell membranes and disrupt the balance of cellular components resulting in a decrease in antioxidant content [81, 82]. Some experiments showed a reduced content of ascorbic acid, anthocyanins, and total phenols along with a decreased antioxidant activity after UV-C treatments for 15, 30, and 60 min [83]. The impact of UV-C processing cannot be accurately predicted and must be evaluated on a case-by-case basis. The effects of this treatment on the levels of beneficial compounds vary, depending on factors like the kind of food matrix, processing conditions (e.g. intensity or duration), and in the case of fruits and vegetables, the variety, climate, and season [84]. As such, more research is necessary to draw reliable conclusions. Therefore, caution should be exercised and preliminary tests should be carried out when considering the application of UV-C technology in the food industry.

Pulsed Electric Field

Pulsed Electric Field (PEF) technology is one of the promising preservation methods in food processing that uses short bursts of high-voltage electricity to deactivate microorganisms in foods. A non-thermal method, PEF is applied to foods to extend shelf life without significantly affecting their nutritional quality, flavor, color, and texture. The technology is based on applying electric fields to foods placed between the electrodes in the chamber for a very short time (typically microseconds to milliseconds) [85]. The electric field develops pores in the cell membrane, leading to increased permeability. This phenomenon, known as electroporation, disrupts cell integrity, leading to the inactivation of enzymes responsible for spoilage or even cell death, thereby extending the shelf life of food products [86]. Therefore, PEF has been referred to as cold pasteurization in the food industry, especially for liquid products such as milk, egg, yogurt, oil, beverages, fruit juices, and soups [87].

Since its invention in the 1950s, PEF technology has been utilized for different purposes, including juice production, extraction of bioactive compounds, microbial inactivation, drying time reduction, and biomass processing [85, 88].

A comprehensive study on the extraction of virgin olive oil from different Spain-originated cultivars with different operating parameters revealed that the PEF treatment gave the best oil yield with short malaxation times at low processing temperatures [89]. Moreover, according to sensory results, PEF-treated oils showed no defect or off-flavor.

Another study applies PEF for olive oil production in a pilot plant scale [90]. It was found that PEF can assist to mechanical extraction methods without changing quality and sensorial properties. PEF even yielded higher phenolic content (oleouropein derivatives). Authors suggested that even if PEF treatment does not require high levels of energy, initial investment should be considered. Carpentieri et al. [91] conducted a study to extract bioactives from oregano and wild thyme with PEF and Ultrasound (US) assisted method [91]. They reported both treatments (PEF and US) yielded noticeably higher phenolic compounds while US was found out to be more cost effective. In study of El Kantar et al. [92] PEF was used as pretreatment before juice extraction from whole fruits or peels stack of orange, pomelo and lemon [92]. According to electron microscopy data, PEF did not cause severe damages in the cell structures of fruits. Yet, PEF was remarkable in increasing polyphenol content especially for the lemon. This was explained with the selective extraction of polyphenols due to electropermeabilization.

There have been studies which PEF was used for different purposes other than extraction such as preservation, or pretreatment before drying or freezing. In the study of Rios-Corripio et al. [93], pomegranate fermented beverage was treated with PEF to compare its effects on microbial, physicochemical and bioactive characteristics with pasteurization (VAT and HTST) [93]. Using PEF on the beverages killed all microorganisms on freshly prepared juices and maintained this effect throughout the storage period. However, while antioxidant capacity was the highest for PEF treated samples, it decreased at a greater extend during storage for the same samples. The reduction in total soluble content for VAT-pasteurized and PEF treated samples was attributed to the caramelization of sugar due to heat and pulse effect. They noted that PEF can be used as an alternative method to conventional pasteurization methods. An interesting study searches effect of PEF treatment on the microbial, physicochemical, and nutritional properties of milk added orange juice [94]. Authors concluded that PEF was very successful to kill microorganisms while preserving juice's taste, color and nutrient property. However, they reported that long processing times are required to satisfy country standards in terms of microbial load. Telfser & Gómez Galindo [95] applied PEF as the pretreatment before drying (air, vacuum and freeze) of basil leaves [95]. They concluded that PEF shortened drying times due to reversible permeabilization for all methods. In fact, PEF application regardless of drying method was found out to be very successful to obtain most fresh leaves in terms of color and smell. Another study aims to improve freezing tolerance of spinach leave by treating with PEF and vacuum impregnation (VI) in the presence of trehalose as cryoprotectant [96]. Authors claimed that even if freezing provides microbial safety, it can damage cell structure by forming ice crystals. Therefore, they applied PEF and VI as pretreatments before freezing and thawing cycles to facilitate the distribution cryoprotectant into cell. They cultivated the spinach under two different temperatures (5 ℃ and 20 ℃). Even though survival rate of the leave was lower for 20 ℃, PEF and VI were reported to keep tissue vitality and improved drastically the freezing tolerance.

High-Pressure Homogenization

With the steadily increasing demand to improve the organoleptic quality and nutritional value of food products, several innovative methods, such as high-pressure homogenization (HPH), which are non-thermal or physical treatments, as alternatives to the conventional ones, have been utilized in the food industry [97–99]. HPH is considered a kind of green technology because it promises short processing time, low carbon dioxide emission, reduced energy consumption, and a process free from pollution solvents [100]. The working principle of HPH technology is to subject fluids continuously to high pressures, up to 300 MPa, forcing them through a narrow gap, which causes shear stress distribution across the food products resulting from cavitation, turbulence, collision, and impingement [98–101]. This energy transformation directly affects the structure of food components [101]. Preparation of emulsions, enhancing the stability and rheological properties of dispersions, reduction of particle size, inactivation of spoilage microorganisms, extension of shelf life, increasing the extractability of phytochemicals, modification of functional properties and improvement of solubility and foaming ability of proteins can be achieved using HPH method in the food industry [54, 98–102].

HPH technology especially plays a key role in Mediterranean foods such as tomato and olive oil, known for their fresh flavors and health benefits in preserving nutritional quality and sensory characteristics. Several studies demonstrated the promising effects of HPH in recovering compounds from tomato peels [103], tomato pomace [104], and the alcohol-insoluble residue of processing tomato [105]. In addition, Van Audenhove et al. [106] and Liang et al. [107] revealed that HPH enhanced the network-forming potential of tomato cell wall material [106, 107]. Liang et al. [107] also determined that the release of lycopene from tomato pulp and its stability and bioaccessibility were improved by HPH treatment [107]. It was also supported in the study of Carpentieri et al. [108] that the extraction of valuable bioactive components such as phenolic compounds and lycopene from tomato pomace increased with the HPH process [108].

Moreover, they showed that HPH reduced the particle size, providing enhancements in the stability of the tomato pomace suspension. HPH technique, on the other hand, has the outstanding capability of nanoemulsions, including olive oil, and it directly affects the particle size of droplets and physical stability [109, 110]. It was also used to produce cellulose-containing nanomaterials from the waste of olive leaves [111]. In addition, the effect of HPH on the structure and functional properties of plant proteins, which are a significant part of Mediterranean ingredients, has also drawn special attention in food science [102, 112]. It was revealed in the studies of [113] and Zhao et al. [114] that the homogenization of pea protein by the HPH method enhanced emulsifying and foaming properties and solubility [114]. In a study by Melchior et al. [115], the improvement of the oil-holding capacity of pea protein and its solubility by HPH was also shown [115]. The promising effects of HPH on the functional properties of Cyperus esculentus L. protein [116], quinoa protein [117], kidney bean protein [118] and lentil proteins [119] were also demonstrated in the related studies. The favorable effects of the HPH process were also investigated on other Mediterranean ingredients such as artichoke [120], citrus fiber [121] and orange juice [122].

Freeze Drying

Fresh foods that have high water content prone to microbial or nutritional deterioration during transportation and storage. Drying is a technique to protect fresh foods for a long time. Drying process can increase the shelf life by reducing microbial growth and deteriorative reactions. Also, it provides convenience during transportation and storage by reducing size and weight of fresh foods [123–125]. There are several different drying techniques, which can affect the quality of the final product. Therefore, choosing appropriate drying methods is important [125]. Freeze drying, also known as lyophilization, is one of the drying techniques which is used to produce high quality dried foods. During freeze drying, water in solid form turns directly into vapor form by sublimation. The drying process consists of 3 steps which are freezing, first drying and second drying [123–126].

The freezing step is solidification of water prior to drying. The primary drying is where sublimation takes place by reducing pressure and supplying necessary heat. The secondary drying step involves desorption of unfrozen water [123, 124]. There are several process parameters such as loading capacity, freezing rate, heating level and pressure value, which affect drying time and final quality of the dried material [126, 127]. Therefore, selecting and controlling appropriate parameters are critical.

Freeze drying is a suitable drying method especially for foods that are susceptible to heat and oxidation. It provides high quality dried products with maximum nutritional values [124]. Hence, numerous studies have been conducted on freeze drying in the literature, and various studies on freeze dried Mediterranean foods are also available. For instance, Tan et al. [128] studied effects of drying methods (freeze drying and oven drying) on chemical components, antioxidant activities and appearance of three different tomato cultivars [128]. As a result of this study, lycopene content was found higher in oven dried tomatoes and antioxidant activity did not change significantly with the different drying methods. On the other hand, freeze dried tomatoes had better appearance and higher polyphenols than oven dried tomatoes. Cecchi et al. [129] studied on the drying processes of pomegranate peel and olive pomace (pâté), and they analyzed polysaccharide and phenolic contents of the dried products [129]. Pomegranate peel was dried at oven dryer with different temperatures. Pâté was dried at oven dryer with different temperatures (50, 70, 90, 110 °C) and freeze dryer at laboratory scales, and also it was dried with industrial dryer at 150 °C. When oven dried and freeze-dried pâté were compared, freeze dried one had better results. Oven drying caused toasted/burnt smell, brown color and higher reduction in total phenolic content as compared to lyophilized pâté. On the other hand, industrial drying at 150 °C provides similar total phenolic content and better preservation of the polysaccharide structure. Also, the sensory properties of pâté were not negatively affected when dried in industrial or freeze dryer. Therefore, freeze drying gave better results than oven drying, but when industrial drying is considered, it provided shorter drying time for large scale production with good results.

Freeze drying is considered quite costly drying method due to its high energy and time consumption [123, 124]. The drawbacks are tried to be reduced by changing the process parameters. However, the proper parameters should be selected according to material to prevent undesirable effects such as melting, shrinkage and loss of nutrition [126]. Characterization of some quality parameters of dried products, like appearance, porosity, nutritional value, moisture content and rehydration ability, can be used to select process conditions [127]. Feng et al. [130] studied the effects of freeze-thawing pretreatment before freeze drying on the quality and drying process of garlic [130]. They have showed that the pretreatment reduced the energy requirement (14.25–15.50%) and drying time (22.22–33.33%) significantly compared to drying of unpretreated garlic. Moreover, they obtained good quality dried garlic after pretreatment with improved flavor, chemical composition and thermal stability. Silva-Espinoza et al. [131] investigated freeze drying process parameters on the quality of formulated orange puree [131]. They changed the freezing rate (slow or fast), shelf temperature (30, 40 and 50 °C) and pressure value (5 and 100 Pa), and the orange puree was dried at 30, 40 and 50 °C for 25, 7 and 6 h, respectively. They concluded that the optimum process parameters of freeze drying are low pressure (5 Pa) and high temperature (50 °C) according to structure and nutritional value of the final dried product. Furthermore, energy requirement to freeze dry formulated orange puree was evaluated in another study to observe the effect of the process parameters. Optimum conditions were found as 5 Pa and 50 °C among different shelf temperatures (30, 40, 50 °C) and chamber pressures (5 and 100 Pa) to produce more economical product by reducing drying energy [132].

To conclude, freeze dryer is a good drying method for obtaining high quality dried foods when process parameters are selected correctly despite its high energy and time requirement [126].

High Hydrostatic Pressure (HHP)

The demand for safe and nutritious food in today's technological era highlights the importance of food processing. While conventional thermal methods help control microorganisms and are commonly used in the food industry, they can be associated with sensory and nutritional loss [133, 134]. Thus, food industry continuously seeks processing technologies that preserve natural flavors and quality, leading to the development of high-pressure processing (HHP).

HHP processing offers a sustainable alternative to traditional thermal methods by significantly reducing water consumption and manpower costs while ensuring microbiological and physicochemical safety, preserving the quality of the end product [135, 136]. Additionally, it has the capacity to enhance nutrient bioavailability and eliminate antinutritional factors, ultimately resulting in higher-quality food products [134, 137]. HHP applications are largely preferred for non-solid products due to significant ease of operation.

HHP demonstrates remarkable efficacy in olive oil production [138–141]. HHP effectively deactivates spoilage enzymes and pathogens when olives are subjected to elevated pressures, exhibiting lower microbial spoilage. Findings of Andreou et al. [139] using virgin olive oils revealed significant improvements in cell disintegration, total phenolic content concentrations, and antioxidant capacities, leading to enhanced extractability of intracellular olive oil, while exhibiting high nutritional content and improved oxidation stability [139]. This suggests that HHP promises potentially superior virgin olive oil with improved yields.

In a similar vein, the utilization of high-pressure application in tomato processing represents a significant advancement in the production of tomato-based products. HHP has demonstrated superior effectiveness in preserving the natural color, flavor, and nutrient composition of tomatoes when compared to traditional thermal processing methods that involve high temperatures [142, 143]. HHP, being particularly well-suited for liquid products, can effectively inactivates pathogenic microorganisms such as bacteria, yeasts, and molds present on the tomato sauce and juice. The high pressure disrupts the cellular structure of these microorganisms, leading to their inactivation or destruction [144–146]. This antimicrobial action helps extend the shelf life of tomato products by reducing microbial spoilage and contamination, thereby enhancing food safety and quality. Additionally, HHP preserves the natural microbiota present in tomatoes, which can contribute to their flavor development and overall sensory characteristics. Consequently, HHP serves as a valuable tool in the production of safe and high-quality tomato-based products with extended shelf life.

Many other products and materials from the Mediterranean region are being subjected to HHP to evaluate viability of use and understand interaction kinetics. Such materials include even fermented products like yogurt, kefir, or alcoholic beverages [147–150]. HHP has been documented to alter sugar consumption and inhibits lactic acid production, influencing pH variation, or completely inhibiting the fermentation process if conducted at pressures above 100 MPa [148, 149]. However, Ferreira et al. [147] extended this by adapting *S. cerevisiae* to sublethal pressures, noting enhanced ethanol production after cycles at 15 and 25 MPa, showing that appropriate pressure modulation with product specific modifications should be investigated further [147].

Overall, the integration of HHP technology in the characterization and reformulation of Mediterranean ingredients proposes valuable shifts in the industry. Manufacturers can uphold the authenticity and nutritional integrity of these foods while meeting safety standards and consumer expectations.

Cold Plasma Technology

Plasma is an electrically conductive medium with an approximately equal number of positively and negatively charged particles created by the ionization of atoms in the gas. In addition to electrons and ions, plasma contains gas atoms, molecules in the ground and excited states, free radicals, quanta of electromagnetic radiation, i.e. UV photons and visible light. Free ions and electrons make the plasma electrically conductive and interactive with electromagnetic fields. There are two types of plasma: equilibrium (thermal) and non-equilibrium (non-thermal) plasma. In non-thermal plasma or cold plasma (CP), the cooling of ions and uncharged molecules is more efficient than the transfer of energy from electrons, whereby the gas remains at a low temperature [151]. CPs are often safe to touch and can be used in combination with heat-sensitive materials. Although temperatures are around room temperature or slightly higher, CP exhibits unique properties required for a wide range of applications in food industry [152–155].

The most significant and widespread application of CP is in the sterilization of surfaces due to its ability to deactivate microorganisms, i.e. to effectively eliminate bacteria, viruses and other pathogens, without damaging sensitive surfaces. However, the mechanisms of inactivation by high voltage atmospheric cold plasma are different for *Escherichia coli* and *Staphylococcus aureus*, for pathogens that are important for the food industry, so treatment should be adjusted [156]. CP technology degrades pollutants and microorganisms due to the presence of reactive species that are formed in the discharged plasma: reactive oxygen species, reactive nitrogen species and OH radicals in plasma discharges play an important role in the degradation of contaminants such as metals, metalloids, VOCs, colors and microorganisms [155]. Atmospheric CP treatment for 10, 60 and 120 s resulted in reduction of *Escherichia coli, Salmonella* and *Listeria monocytogenes* populations on tomato to undetectable levels from initial populations [157]. Microwave-powered CP treatment 2–10 min at 400–900 W was used for improving microbiological safety of cherry tomatoes against *Salmonella* and without affecting their biological properties [158]. CP processing technology for food preservation has a recognized potential to simultaneously meet consumer demands and deliver high-quality processed food with extended shelf life, without additives and without thermal processing [159, 160]. Dielectric barrier discharge atmospheric CP treatment (35 kV, 1.1 A, 3 min) at 10 and 25 °C inactivated of *Salmonella* and increased the storability of grape tomato without effects on the surface color, firmness, weight loss, lycopene concentration and residual ascorbic acid of grape tomatoes during storage [161]. Effects of dielectric barrier discharge CP treatments (10 kHz, 0–5 min, air) on degradation of anilazine fungicide and quality of tomato (Lycopersicon esculentum Mill) juice were found and with the increase in treatment time, the difference in the total color value of tomato juice increased significantly, which might be due to the decomposition of carotenoid pigments by plasma species [162]. Atmospheric CP treatment on vitamin C in tomato beverages showed that the vitamin C retention rate was the highest after 10 min of CP treatment, reaching 95% [163]. Treatment with CP technology showed a decrease in enzyme activity in treated extra virgin olive oil without harmful changes in volatile and phenolic profiles and without significant changes in color, antioxidant activity and preoxide value [164]. CP is a promising non-thermal technology for the extraction of natural pigments, which requires the optimization of the extraction process, i.e. the operating conditions of plasma production for each case separately and with the monitoring of the changes caused by the plasma on the molecules of chlorophylls, carotenoids, anthocyanins and betalains [165]. The combination of using atmospheric CP technology and natural antimicrobial agents such as grape seed extract proves to be a good alternative to conventional food decontamination methods, without the use of chemical preservatives or antibiotics [166]. It is possible to modify the structure of food and introduce specific functionality using CP: modulation of the hydrophobicity or hydrophilicity of the food surface [167]; inactivation of enzymes as a modification of functional properties [168, 169]; modification of the protein structure [170]. Atmospheric CP shows the greatest potential: in the process of removing biological agents [168], toxins or surface contamination from food and surfaces with which food comes into contact [171], in the modification of packaging materials [172, 173], in improving the functionality of food ingredients [174, 175], and in the decontamination of water and wastewater in food production [176]. Multiple applications of CP technology in food processing enable the improvement of production process performance, food safety and sustainability as an imperative for the future [177–179]. CP is used as a preparative analytical technique that enables a more sensitive classification of adulterated olive oil because non-thermal discharges are the source of highly oxidizing species, and oxidation induced by CP triggers unique mechanisms of lipid oxidation depending on the specific composition of the oil matrix and other ingredients [180, 181]. Plasma is characterized by the ability to deactivate the peroxidase enzyme in tomatoes. By using air plasma, various active species and radicals are produced with the possibility of performing chemical reactions, which leads to chemical changes in amino acid chains, causing a decrease in enzyme activity. At the same time, due to the low temperature of the reaction, the nutritional content is retained [182]. By combining the ultrasonic synthetic method and CP treatment, good effects on the antibacterial and physicochemical properties of tomato juice are obtained without a negative effect on the color of the juice [183]. Plasma jet is used to reduce the microbial load in tomatoes, whereby contaminants are reduced to immeasurable levels, and the sensory properties remain unchanged. The treatment also significantly extended the shelf life of tomatoes, and it was carried out at low temperatures [184]. The development of consumer awareness and preference for healthy food that is raw or non-thermally processed has encouraged the development of CP technology [185, 186]. It is used to improve the microbiological quality and to prevent rapid physical, chemical and sensory changes, which results in better quality foods [187–189] with an extended shelf life [190, 191]. The combination of CP technology with other new technologies such as pulsed electric field, pulsed light, ultrasound and nanotechnology gives even better results in food processing [192, 193].

Table 1 summarizes the application of various novel technologies in the reformulation of Mediterranean ingredients.

Characterization of Mediterranean Ingredient by Novel Technologies

Nuclear Magnetic Resonance (NMR)

The food industry has experienced a paradigm shift in analytical methods in recent years due to the introduction of new techniques like Nuclear Magnetic Resonance (NMR) spectroscopy and relaxometry as powerful instruments for quick and thorough analysis. Particular attention has been paid to how these techniques help with nutritional profiling, quality assurance, and authenticity evaluation [194–196]. In ^{1}H NMR (proton nuclear magnetic resonance) spectroscopy, the idea is related to the magnetic characteristics of hydrogen nuclei, or protons [197]. During the process, the alignment of hydrogen nuclei due to an external magnetic field occurs to produce different energy levels in the sample. Protons absorb energy and move between the energy levels when exposed to radiofrequency pulses. When the pulses stop, the protons revert to their initial states and release energy that is identified as an NMR signal. These signals are utilized to create a spectrum that provides details on the chemical environment of hydrogen atoms in a sample. Water, lipids, proteins, carbohydrates, and other food components can all be analyzed simultaneously using NMR spectroscopy [198]. This technique also makes it possible to identify and quantify various chemicals, resulting in a thorough understanding of food composition [199]. NMR relaxometry, a subset of NMR spectroscopy, focuses on measuring the relaxation times of nuclear spins in a sample [200]. This approach has been extensively used in many areas of food science because of its rapid analysis of physicochemical parameters such as water distribution, hydration behavior, solid fat contents, crystallinity, and moisture content of food products [196, 201–203].

Mediterranean-based diet is well known for its flavorful cuisine and health benefits [204]. In recent years, NMR has proven to be a powerful method for interpreting the molecular complexes of key Mediterranean ingredients, including tomatoes, olives, herbs, and spices [205–208]. In a study, Time Domain NMR (TD-NMR) was applied to tomatoes with a focus on characteristics like color, soluble solids content (SSC), and defects [209]. The study tried to develop precise and nondestructive classification models by combining computational techniques with TD-NMR. Remarkably, varied decay times were noted for every class; green tomatoes, for example, showed a shorter decay signal than red tomatoes, which was associated with water mobility in various tissue compartments. The results showed how useful TD-NMR is for screening applications before processing and how accurate sample categorization in the tomato processing sector can be achieved by applying CPMG decay times. Not only the tomato itself but also its components were examined with NMR. In one research, NMR relaxometry was employed to explore the proton relaxation distribution in tomato seeds, evaluating the effects of osmotic stress, ultrasonication, and high hydrostatic pressure on cell membrane integrity [208]. With varied NaCl concentrations, ultrasonication durations, and pressure levels, the NMR spectra revealed four peaks indicative of distinct water proton compartments within the plant cell. The study found that NMR relaxometry was an effective method for examining the cell integrity of tomato seeds subjected to various treatments, providing insightful information about the extent of cellular damage.

The examination of olives, one of the most important foods of Mediterranean culture, using NMR has been also a major area of research. Most of the studies have examined the metabolic profile of the edible olives to investigate how NMR can be used to evaluate various cultivars, geographical origins, and processing methods that affect a product's flavor, aroma, and nutritional value [206–210]. Besides, NMR was utilized to learn more about the oxidation status, fatty acid composition fluctuations, and olive oil quality [211–214]. Examining these characteristics is essential to evaluate the data and verify the nutritional value and authenticity of olive oil. For spices and herbs, NMR spectroscopy using a chemometric approach has proven to be a useful technique, just like in the case of olives and their components. Significant volatile molecules that contribute to different flavors and factors influencing the sensory qualities of herbs and spices have been examined through the use of NMR methods [207, 215, 216].

In recent years, there has been a noticeable increase in the popularity of plant proteins especially derived from Mediterranean cuisine due to growing awareness of sustainability and health [217]. Accordingly, the plant proteins from seeds and legumes that are used in Mediterranean cuisine, such as peas, chickpea, lentils, pumpkin seeds, and sesame seeds generated a great deal of interest in NMR studies [218–221]. Through the examination of relaxation periods, these studies have investigated the hydration dynamics of these proteins to assess their integration into functional foods and distinguish between their structural and functional properties. The findings indicated that NMR, which is quick, accurate, and

Table 1 Reformulation of Mediterranean ingredients by novel technologies

Method	Samples	Application	References
Semi-industrial continuous microwave system	Tomato Puree	Higher total antioxidant capacity and vitamin C content, enhanced viscosity and lycopene extraction, lower residual enzyme activity	[21]
Industrial scale microwave pasteurizer	Tomato Juice	Similar physicochemical and microbiological characteristics, higher initial antioxidant activity, better cytoprotective effect	[23]
Microwave	Tomato Puree	Similar flavor, color, and overall acceptability, 5-log reduction in E. coli, similar lethality values	[22]
	Olive Fruits	Significantly reduced lipase activity, increased stability of olive oil during storage, no significant differences in chemical composition	[24]
	Lentil Flour	Better water and oil absorption capacity, enhanced emulsification properties due to protein denaturation	[25]
Microwave-Vacuum Drying	Tomatoes	Investigated the effect of microwave-vacuum drying on the physicochemical properties, including texture, color, and nutrient retention, of a functional tomato snack bar.	[36]
		Evaluated the applicability of vacuum-microwave drying for tomato fruits, focusing on energy cost, color retention, preservation of functional components, and sensory qualities.	[33]
	Olives	Examined the effect of microwave-vacuum drying on the drying kinetics and quality of olive slices, focusing on texture, color, and antioxidant properties.	[30]
	Sugar beet	Studied the effects of microwave-vacuum drying on the physicochemical properties of sugar beet sugar, and efficiency of the device.	[35]
	Herbs and spices	Assessed the influence of microwave-vacuum drying on the quality and volatile compounds of Mediterranean herbs, focusing on flavor and aroma retention.	[32]
	Beetroots	Researched combining convective and vacuum-microwave drying for beetroots, finding that this approach enhances efficiency and preserves quality better than traditional methods.	[31]
High Intensity Ultrasound	Tomato juice	Attenuation of *Limosilactobacillus reuteri* DSM 17938 using ultrasound to prevent changes in a probiotic tomato juice	[306]
		Improvement of tomato juice concentration process	[307]
		Inactivation of mesophilic aerobic microorganisms, lactic acid bacteria, coliform bacteria, and yeast	[52]
	Fresh tomatoes	Reduction of *Listeria monocytogenes* and *Salmonella Newport*	[308]
		Increase in accumulation of secondary plant metabolites during storage time	[309]
	Tomato seeds oil - based ice cream	Pasteurization and homogenization of innovative ice cream product based on Oleogels obtained from tomato seeds oil	[310]
	Extra virgin olive oil	Stabilization of organic extra virgin olive oil	[311]
	Virgin olive oil	Improvement of extraction efficiency	[312]
	Olive pomace oil	Increase in the bioactive potential after ultrasound assisted maceration	[313]
Ultraviolet-C (UV-C) Light	*Gelim* black olives	Log reductions in total aerobic count and yeast and mold counts of 0.53-1.71 and 0.31–1.43 CFU/g, respectively	[60]
	Cauliflower	1 log reduction of *Listeria monocytogenes,* 0.7 log reduction of *Escherichia coli*, and 1 log reduction of yeasts and molds	[68]

Table 1 (continued)

Method	Samples	Application	References
	Durum wheat semolina	Increasing water absorption of semolina dough for improved dough yield and reduced staling and shrinkage of flour products	[65]
	Date fruit powder	Increased content of phenolic compounds from 20.97 to 111.62 mg/100 g after 20 minutes of UV-C exposure	[80]
	Tomatoes	Increase in lycopene content after 21 days of post-harvest storage with minimal impact on the color, texture (i.e. hardness) and °Brix	[314]
	Immature green tomatoes	UV-C applied to each of the two sides of the fruits for 1 h (dose of 2 J/cm^2/side) led to a 5.23-fold increase in lycopene content, a 1.5-fold increase in total carotenoid content, and a 1.3-fold increase in phenolic content	[315]
	kailan-hybrid broccoli	UV-C dose of 2.5 kJ m^{-2} led to a 2.61, 1.22 and 0.72 log reduction in the populations of *Salmonella Enteritidis, Escherichia coli* and *Listeria monocytogenes*, respectively	[316]
	Strawberries	Enhanced antioxidant capacity linked to an increase in the polyphenol content (flavonoids, anthocyanins, fisetin, and pelargonidin) after 16.5 minutes of UV-C exposure at 1.2 W/m^2 dose	[317]
	Orange-Tangerine Juice	*Saccharomyces cerevisiae*, *Lactiplantibacillus plantarum*, and *Escherichia coli* were reduced by 1.6, 2.4, and 3.8 log cycles, respectively	[318]
	Brocolli	10%, 13%, and 14% increase in total phenolic content, antioxidant activity and ascorbic acid, respectively	[319]
Pulsed Electric Field (PEF)	Olive Oil	PEF increased the oil extraction yield with short malaxation times at low processing temperatures	[89, 90]
		PEF was successful to assist mechanical extraction methods without changing quality and sensorial properties. PEF application even yielded higher phenolic content.	[90]
	Oregano and wild thyme	PEF increased bioactive extraction yield	[91]
	Orange, pomelo and lemon	PEF was used as pretreatment before juice extraction and did not cause severe damages in the cell structures of fruits. PEF was remarkable in increasing polyphenol content especially for the lemon	[92]
	Pomegranate beverage	PEF killed all microorganisms on freshly prepared juices and maintained this effect throughout the storage period	[93]
	Basil leaves	PEF shortened drying times and was found out to be very successful to obtain most fresh leaves in terms of color and smell	[95]
	Spinach	PEF was applied to improve freezing tolerance. PEF kept tissue vitality while improving the freezing tolerance.	[96]
High Pressure Homogenization	Tomato peel	Increased the release of intracellular compounds and water-insoluble lycopene	[320]
		Reduced oil-water interfacial tension	
		Increased antioxidant activity	
	Tomato pomace	Increased cellulose isolation yield	[104]
		Increased phenolic compounds in side streams	
		Enhanced morphological and functional properties	
	Tomato pomace	Reduced particle size	[108]
		Reduced surface tension	
		Increased antioxidant activity, total phenolic content, dietary fiber content	
		Enhanced lycopene stability	

Table 1 (continued)

Method	Samples	Application	References
		Enhanced lycopene bioaccessibility during intestinal digestion phase	
	Tomato pulp	Increased the release of lycopene	[107]
		Reduced particle size	
		Increased homogeneity and turbidity	
		Enhanced lycopene stability and bioaccessibility	
	Processing Tomato	Increased pectin solubilization and extractability	[105]
		Increased purity, molecular mass and amount of rhamnogalacturonan I domains	
		Increased hemicellulose and cellulose content in unextractable fractions	
		Enhanced functional properties	
	Tomato cell wall material	Increased pectin solubilization and extractability	[106]
		Enhanced viscoelastic properties	
		Enhanced network forming potential	
		Increased water binding capacity	
	Extra virgin olive oil-in-water nanoemulsion	Determination of optimum conditions for emulsfying agents, lecithin and Tween 20	[109]
		Effects of homogenization pressure and cycles on stability, droplet diameter and polydispersity index	
	Olive leaf waste	Production of nanocellulose and characterization of morphology, chemical composition, thermal, colloidal properties and crystallinity	[111]
	Pea Protein	Reduced particle size,	[114]
		Increased solubility and in vitro antioxidant activityEnhanced stability	
		Enhanced emulsifying and foaming properties	
		Increased solubility, surface hydrophobicity and intrinsic fluorescence	
		Reduced particle size	
		Enhanced emulsifying and foaming properties	
		Effects of homogenization pressure on protein unfolding, protein aggregation and functionality	
		Increased solubility, oil holding capacity and digestibility	[312]
		Enhanced emulsifying properties	[115]
	Cyperus esculentus L. protein	Reduced β-sheet content	[116]
		Increased α-helix and random coils	
		Increased absolute value of Zeta potential	
		Reduced particle size	
		Reduced apparent viscosity and increased fluidity	
		Enhanced emulsion stability	
	Quinoa protein	Reduced particle size	[117]
		Reduced oil droplet size with increased quinoa protein isolate concentration	
		Enhanced emulsion stability and gel strength with increased quinoa protein isolate concentration and heat treatment	
	Kidney bean protein	Effects of homogenization pressure on intramolecular interactions, particle size, molecular weight, viscosity, emulsifying properties and stability	[118]

Table 1 (continued)

Method	Samples	Application	References
	Lentil protein	Effects of homogenization pressure on unfolding of protein, solubility, emulsifying and foaming properties	[119]
		Reduced particle size	
		Enhanced functional properties	
Freeze drying	Tomato	Analyzing effects of freeze drying and oven drying on properties of different tomato cultivars.	[128]
	Olive pomace	Comparison of freeze drying with oven drying at lab scale and freeze drying with industrial drying system by studying on phenol and polysaccharide content of the final product.	[129]
	Garlic	Monitoring effects of freeze-thawing pretreatment on the drying process and quality of the dried garlic.	[130]
	Formulated orange puree	Investigating impacts of freezing rates, shelf temperatures and pressure on quality of the final product.	[131]
		Studying effects of pressure and shelf temperature on energy consumption.	[132]
High Hydrostatic Pressure (HHP)	Olive oil	Optimizes HPP to enhance olive oil yield and quality. Increased yield, improved phenolic, and boosted a-tocopherol, enhancing oxidative stability and reducing malaxation time and temperature.	[322]
	Table olives	Monitors acrylamide and phenolic compounds in table olives after high hydrostatic pressure (HHP) and cooking treatments. Acrylamide is not found after HHP but forms during frying and baking, with frying causing less acrylamide and phenolic loss than baking. Fresh olives are best for high phenolic intake and reduced acrylamide.	[141]
	Tomato	Impact of thermal and pressure-based technologies on the retention of carotenoids and the quality attributes of tomato juice. Minimal color changes after high-pressure processing at 600 MPa/45°C/5 min.	[323]
	Tomato sauce	The study evaluates high hydrostatic pressure (HHP) treatment on enriched tomato sauce, focusing on quality changes and nutrient retention. HHP increases total phenolic content, retains higher lycopene compared to thermal pasteurization, and causes no significant change in color parameters.	[324]
	Tomato	The study investigates the effect of high hydrostatic pressure (HHP) on the carotenoid profile and lipophilic antioxidant capacities of tomato purées, finding that HHP enhances antioxidant capacity but reduces lycopene and β-carotene concentrations.	[137]
Cold Plasma Technology	Tomato	Atmospheric CP treatment for reduction of Escherichia coli, Salmonella and Listeria monocytogenes populations	[325]
		Microwave powered CP treatment for improving microbiological safety	[158]
		Dielectric barrier discharge atmospheric CP treatment for microbiological safety and preservation	[161]
		Dielectric barrier discharge CP treatment for degradation of anilazine fungicide	[162]
		Dielectric barrier discharge for tomato peroxidase inactivation	[182]
		Intermittent corona discharge plasma jet for microbial load reduction	[184]
		CP treatment impacts on physicochemical characteristics	[188]
		Inactivation of microorganisms with CP treatment	[326]

Table 1 (continued)

Method	Samples	Application	References
	Tomato Juice	Atmospheric CP processing on quality parameters	[163]
		Combining ultrasonic synthetic method and CP treatment for preservation	[183]
		Changes in ascorbic acid, sugars, phenolics, carotenoids induced by CP application	[189]
	Olive Oil	CP effects on the lipoxygenase enzyme activity, aroma and phenolic profiles of olive oil	[164]
		CP as preparative analytical technique for olive oil adulteration	[180, 181]
	Herbs and Spices	CP treatment for decontamination	[327]
		Effects of CP on chlorophylls, carotenoids, anthocyanins, and betalains in natural pigment extraction	[165]
	Plant Proteins	Cold atmospheric plasma processing on the techno-functional protein properties	[170]

non-destructive, could be an alternative approach for looking into hydrated water on molecules, which are known to be difficult to analyze through conventional methods.

NMR has also been used to investigate more complex and functional foods reformulated with Mediterranean ingredients, including tomato sauces, juices, and snack bars. In the study of Gul et al. [36], tomato snack bars enriched with olive powder and pea proteins were analyzed through NMR relaxometry [36]. The aim was to evaluate how various drying techniques affected the distribution of water in the samples. By studying T_2 relaxation times, the study found that microwave vacuum dried samples had shorter T_2 times than conventional dried samples. All things considered, the NMR relaxometry supplied information about the dynamics of water distribution that are impacted by various drying techniques with the contribution of different ingredients. In another study, TD-NMR was used to examine the composition of a novel functional tomato sauce enriched with tomato peel powder, olive powder, and pea protein [222]. Following analysis of the T_2 relaxation times data, it was discussed that tomato peel powder and pea protein content had a substantial impact on T_2 times, with a decrease noted as their concentrations increased. This indicated that both components reduced molecular mobility, leading to faster relaxation times. The results demonstrated a match with the other experiments such as rheology and solubility, indicating that NMR supplies valuable information when used in conjunction with other experiments.

The use of NMR to investigate Mediterranean foods by themselves and interaction in a complex matter has gained popularity in recent years. As technology advances, more study is expected to enhance these techniques and offer novel molecular insights. In conclusion, NMR is a priceless analytical tool that offers a comprehensive and non-invasive way to dig into the molecular mysteries of Mediterranean foods.

Electron Paramagnetic Resonance (EPR)

EPR (electron paramagnetic resonance) or ESR (electron spin resonance) is a spectroscopic technique for studying the chemical species characterized by at least one unpaired electron. The principle of EPR spectroscopy is similar to that of NMR spectroscopy, but EPR is based on the splitting of electronic spin states, whereas NMR detects the splitting of nuclear spin states. Since detection is not dependent on color, porosity, or aggregate state, EPR is widely used as a unique, direct, non-destructive, and very sensitive technique for the identification, quantification, and characterization of free radicals in food systems based on monitoring the interactions of unpaired electrons [223–225].

However, the EPR spectra are often very complex due to the hyperfine structure that forms in the presence of neighboring magnetic nuclei, such as ^{1}H, ^{13}C, ^{14}N, ^{19}F, etc. Food systems with Mediterranean ingredients also exhibit a complex nature. Therefore, this paper presents different approaches to increase the useful information obtained by EPR spectroscopy for food characterization. These approaches are based on directly detecting and identifying endogenous metal ions or organic radicals in the food, EPR labeling with spin probes, and EPR spin-trapping techniques. These three main methods, in addition to their non-destructive nature and high sensitivity [224, 226, 227] of EPR, are, therefore, further advantages for the versatility of the application. The EPR signal of stable radicals formed in food could be monitored directly, while unstable radicals can be measured indirectly by adding spin traps.

EPR spectroscopy has been successfully used to directly detect biologically important metal ions (iron, copper, manganese, molybdenum, chromium) in food and determine their oxidation states. This is very important in food production to assess the suitability of the metal content for human or animal consumption. The content of manganese is of particular interest as it occurs as a micronutrient in almost all foods of plant origin and in the soil, but also as a heavy metal whose excess can have a toxic effect on plants. Manganese occurs in the soil in a wide range of oxidation states, with its solubility depending on soil pH and redox conditions, and is mainly taken up by roots as Mn (II). In a study by Kostova and co-authors [227], the oxidative state of manganese, i.e., Mn (II), has been confirmed by EPR investigation of the amount of Mn (II) that is accumulated in tomato plant itself, stems, leaves and fruits to gain insight into the role of chemical composition [227]. Subbaiah Kotakadi et al. [228] determined the presence of Fe^{3+} ions in rhombic symmetry and the presence of Mn^{2+} ions in the divalent state in leaves of Spinacia oleracea, one of the main components of the Mediterranean diet, as well as in *Hibiscus sabdariffa* and *Amaranthus gangeticus* [228]. The EPR spectra exhibited the presence of these Fe^{3+} and Mn^{2+} ions, which help in the oxidation-reaction of many carcinogenic free radicals like superoxide. In addition to the metal ions, the sharp signal centered at $g = 1.98$ has been observed. This signal corresponds to the usual organic radical, probably due to the C-O carboxyl radical. The exposure of food in atmospheric oxygen or the food preparation processes can form persistent organic radicals in food. Mainly, these are stable carbohydrate radicals, quinones, and stable semiquinone radicals naturally occurring in plants produced by the oxidation of polyphenolics [229, 230]. These findings provide important insights into metabolic processes and the absorption of nutrients, and consequently, into human health.

The most common and well-known application of EPR spectroscopy is the identification of free radicals formed after applying various food processing methods, including ionizing radiation, frying, grinding, and novel methods like high pressure, pulsed electric fields, ultrasound, cold plasma treatment, and microwaves. Therefore, EPR spectroscopy is an already established method for detecting free radicals induced by ionizing radiation and trapped in the dry parts of irradiated food, as well as an established method for identifying and detecting food sterilized by gamma irradiation [229–231]. The same methods have been developed for successfully detecting and controlling radiated tomatoes and other spices, fruits, and vegetables belonging to the group of Mediterranean ingredients [231, 232]. In addition, transient free radicals are often formed during food processing, especially when heat or ultrasonic processes are used and sterilization with ionizing radiation. Reactive oxygen species (ROS) are most frequently formed, especially hydroxyl and superoxide radicals [233–235]. The concentration of generated transient free radicals is usually below the limit of detection of EPR spectroscopy, so indirect methods are needed for identifying and quantifying of species present [236, 237].

The concentration of free radicals generated during food processing can be assessed indirectly using two types of compounds: spin traps and spin probes. Spin traps react directly with the generated free radical by addition to the molecule, thus forming a stable free radical adduct that can be detected and quantized using EPR spectroscopy. Depending on the radical, different adducts form with different EPR spectra (Fig. 1a). Spin probes also react with the free radicals via a redox process, generating a stable free radical (Fig. 1b).

Spin traps are most commonly some cyclic or aromatic nitrones, where various structural modifications can adjust the polarity and cell permeability of the compound. For example, the cell-permeable hydrophilic spin trap 5,5-dimethyl-1-pyrroline-N-oxide, 2,2-dimethyl-3,4-dihydro-2*H*-pyrrole 1-oxide (DMPO) is frequently used for trapping O, N-, C- and S-radicals both in vivo and in vitro conditions, while N-*tert*-butyl-α-phenylnitrone (PBN) is hydrophobic and more suitable for spin trapping studies in non-polar media. α-(4-pyridyl 1-oxide)-N-*tert*-butylnitrone (POBN) is a hydrophilic analog of the PBN spin trap [238] (Fig. 2a and c). DMPO and its analogs are preferred due to larger differences in EPR spectra of spin trap adducts [239, 240]. Spin probes, most often cyclic hydroxylamines such as 1-hydroxy-3-methoxycarbonyl-2,2,5,5-tetramethylpyrrolidine (**CMH**), 1-hydroxy-3-carboxy-2,2,5,5-tetramethylpyrrolidine (**CPH**) or 1-hydroxy-4-methoxy-2,2,6,6-tetramethylpiperidine (**TMH**), are oxidized into nitroxyl radicals in reactions with ROS and cannot be used to differentiate between different types of free radicals [241, 242].

Unlike direct EPR, spin trap methodology depends on the absolute fidelity of the spin trap reaction. The reaction kinetics of spin traps/probes with ROS and RNS species varies wildly with solvent polarity, temperature, viscosity, and other reaction conditions, so the precise control of the experimental parameters is crucial for intercomparison of results between different treatments [243, 244]. Ideally, the speed of the radical entrapment reaction is the fastest process, and all of the ROS generated are quantitatively converted into stable free radicals that can be analyzed by EPR spectroscopy. ROS and RNS species are known for their short half-lives (less than a millisecond) and low concentration levels in biological systems [245, 246].

A varied mixture of antioxidant species further complicates the quantitative determination of generated free radicals due to the reaction with the stable free radicals generated from spin traps/probes. One should also consider the half-life of the stable radical adducts/products in aqueous solutions, which, while significantly longer than those of ROS, is 35–80 s [245]. Yue Qian et al. [247] have found that extraction of 5,5-dimethyl-1-pyrroline-N-oxide- Reactive Oxygen Species (DMPO-ROS) adducts prolongs their stability up to 10 h [247]. Spin trapping has been most commonly used to characterize the oxidative stability of oils before and after processing and lipid oxidation in general or when using extracts from medicinal and aromatic plants to improve the nutritional value and oxidative stability of vegetable oils [247], with Mediterranean olive oil being the most commonly studied oil [248].

The customary EPR application in the food industry is the measurement of the antioxidant capacity of foods. In the Mediterranean diet, antioxidants play an important role in health protection. Antioxidants reduce the risk of chronic diseases such as cancer and heart disease. DPPH (2,2-diphenyl-1-picrylhydrazyl) is a free radical commonly used to test the ability of compounds to act as free radical scavengers or hydrogen donors and to assess antioxidant activity. The DPPH assay method is based on reducing DPPH radicals by antioxidants and is a rapid and simple method for measuring the antioxidant capacity by EPR spectroscopy in foods [249]. This is paticulary important for monitoring changes in antioxidative activity after use of non-thermal treatments like HIU [250] and HVED [251, 252] or for monitoring temperature-induced changes like histamine production, lipid peroxidation and antioxidant parameters in sardine during storage [253]. Mediterranean ingredients have been studied for different reasons: to monitor the quality of extraction [254], tomato waste [255] or the influence of drought and elevated ozone levels on the free radical contents of fruit from tomato [256].

Near Infrared Radiation (NIR) Spectroscopy

Near Infrared Radiation (NIR) Spectroscopy has become increasingly popular for quality control and analysis for agricultural products, pharmaceuticals, food safety, and food characterization [257]. It is an ideal alternative for complex chemical analysis methods that are particularly fast, non-destructive, and require minimal preparation [258]. NIR is usually performed in the wavelength range between 780 and 2500 nm [259]. This spectral region contains the vibrational overtone and combination bands of molecules, making it ideal for characterizing hydrogen-containing bonds (e.g., C-H, N–H, O–H) in many organic compounds. These features allow NIR spectroscopy to analyze components such as water, protein, fat, and carbohydrates in a rapid and non-destructive [259]. In recent years, research has been conducted to determine the quality parameters of various areas using NIR spectroscopy. It is commonly used to determine the quality parameters of products such as olive oil, tomato, herbs, and grains that form the basis of the Mediterranean diet.

Moreover, critical quality parameters such as protein, fat, and moisture content could be determined quickly, and it is possible to monitor the quality during storage [260–262]. In particular, determining phenolic compounds and antioxidant capacity in olive oil, vitamin and mineral content in fruits and vegetables, and protein, fiber, and essential nutrients in whole grains is very important [263–265]. Methods used to analyze Near Infrared (NIR) Spectroscopy data play a vital role in understanding the results. In particular, multivariate regression analyses such as Partial Least Squares Regression (PLSR) model relationships between complex spectra parameters [266]. Support Vector Machines (SVM) excel in areas such as food authenticity and accurate classification of different food products [267, 268]. Artificial Neural Networks (ANN) exhibit superior performance in modeling complex and non-linear relationships by being used to predict quality parameters such as the degree of ripeness or freshness of fruits and vegetables [269]. These techniques and advances in processing and analyzing NIR spectroscopy data enable industries to optimize quality control processes.

Tomatoes, the first product that comes to mind regarding ingredients of the Mediterranean diet, have been studied many times using NIR spectroscopy. The amount of lycopene in tomatoes was measured by the NIR method [258, 270, 271]. In the study of S. Li, Wang et al. [271] focused on the online detection of lycopene content in two different tomato cultivars by using multipoint full transmission Vis–NIR spectroscopy [271]. To improve the correlation between the spectrum and lycopene content, several preprocessing techniques were used, including Savitzky-Golay smoothing (SG), multiple scattering correction (MSC), and standard normal variable transformation (SNV). The quantitative association between spectral data and tomato lycopene values was established using the Partial Least Squares Regression (PLSR) model. The optimization of characteristic wavelength for lycopene in tomato was also studied [272]. 4 different

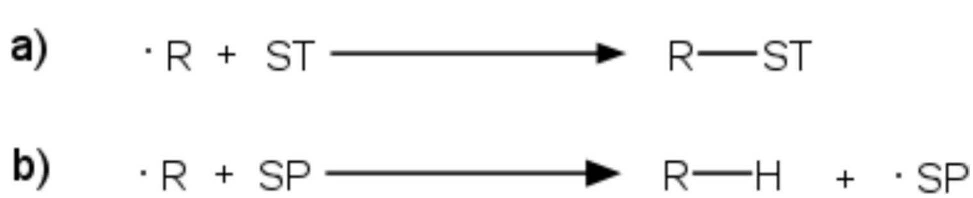

Fig. 1 Reaction of transient radical (R) with a) a spin trap (ST) and b) a spin probe

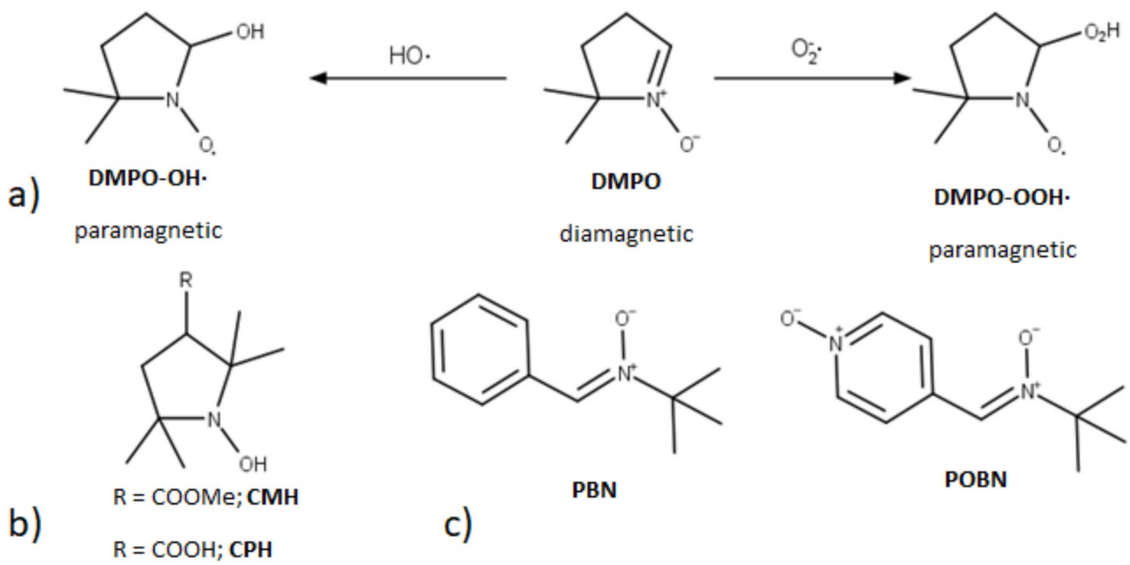

Fig. 2 a) Spin trap 5,5-dimethyl-1-pyrroline N-oxide (**DMPO**) generates radicals with distinct EPR spectra depending on the type of transient radical it captures. Spin probes (b), on the other hand, produce the same stable radical species regardless of the type of transient radical. c) Chemical structures of N-tert-butyl-α-phenylnitrone (**PBN**) and α- (4-pyridyl 1-oxide)-N-*tert*-butylnitrone (**POBN**)

methods (Backward Interval Partial Least Squares (Bi-PLS), Synergy Interval Partial Least Squares (Si-PLS), Uninformative Variable Elimination Partial Least Squares (UVE-PLS) and Genetic Algorithm Partial Least Squares (GA-PLS)) were studied. GA-PLS method was identified as the best method for selecting characteristic wavelengths and optimizing the prediction model. Moreover, the determination of soluble solid content (SSC) and firmness value of tomato by NIR have been studied in several studies [271, 273–280]. In the latest study, two different tomato varieties were gathered at various stages of maturity, and samples were divided into calibration and prediction sets using a systematic process. The spectral data was preprocessed using multiple ways to improve its quality, and distinctive wavelengths for SSC detection were extracted using the least angle regression method. The outcomes showed that the SSC determination for both tomato types was successful [271]. In another study, the soluble solid content (SSC) in different fruits with varying skin thicknesses was measured by NIR spectroscopy [278]. The study developed prediction models for calculating fruits' soluble solid content (SSC) using partial least squares regression (PLSR) modeling. Tomatoes exhibited a low coefficient of determination in the prediction model for SSC, even though it has thin skin and high moisture content. This low correlation was attributed to the impact of water absorption, which led to noise in the measurement. Taste-related compounds of tomato were also studied using IR spectroscopy [281]. Soluble solids, sugars like fructose and glucose, and acids, citric, malic, and glutamic acids found in tomatoes are among the taste-related substances. These chemicals greatly influence the flavor profile and overall perception of tomatoes. PLRS analysis assessed the Root Mean Square Error of Prediction (RMSEP) values and the coefficient of determination (R^2) for each taste-related compound. R^2 of the models ranged from 0.32 to 0.82, suggesting a good fit for the data modeling. In addition, the ripening of tomatoes was studied with the NIR spectroscopy [243, 258, 282]. In the study of Nakashima et al. [243], handheld NIR equipment was used to monitor the ripening of mini tomatoes from their daily changes [243]. NIR spectroscopy was employed to convert reflection to absorption spectra for quantitative analysis of water, sugars, and some pigments such as chlorophyll a, carotenoids, and lycopene. The study compared changes in pigment band areas obtained from NIR spectra with color values (a* and b*) to understand the relationship between biochemical changes and color development during ripening. The changes in chlorophyll content during the ripening process were quantitatively assessed with NIR data. The band area around 670 nm, associated with chlorophylls, was monitored to track the variations in chlorophyll levels over time. Furthermore, the sensory qualities of tomatoes were also studied [283, 284]. In the study of [283], 19 different sensory attributes (sweetness, umami, flavor, mouthfeel, texture, odor, etc.) were analyzed by Gas Chromatography-Mass Spectroscopy (GC–MS), and NIR spectroscopy was used to understand the results [283, 99]. PLSR models were constructed, and the stepwise selectivity ratio (SWSR) method was applied for variable selection to comprehend the sensory attributes. PLSR models function effectively in predicting sensory qualities, especially for sweetness, since they are built using informative wavelengths chosen by the SWSR method. Principle Component Analysis (PCA) was also conducted to intercorrelate the sensory scores of different sensory properties, especially sweetness, umami, saltiness, and tingling, as well as the number of metabolites and spectral absorbance of wavelengths. Detection of pesticide residues in tomatoes is another important topic that has been worked with NIR spectroscopy [285]. Various spectral preprocessing methods were applied in the 460–1050 nm spectrum range to stabilize the models. Key indicators such as correlation coefficients (R), root mean square errors of calibration (RMSEC), and root mean square errors of prediction (RMSEP) were used to evaluate the accuracy of the model. Among the eight combined models developed (PLSR, ANN, PCA, and RF), the SPA-ANN model performed best, with high R, RMSEC, and RMSEP values.

The quality characteristics of olive oil, an important part of Mediterranean ingredients, have also been studied using IR spectroscopy [286–293]. This study conducted by Arroyo-Cerezo et al. [287] explains how important quality parameters such as acidity, peroxide value, 232 nm and 270 nm absorbance values, and fatty acid content in extra virgin olive oil (EVOO) were measured by NIR spectroscopy [287]. NIR detects absorption bands of chemical bonds in fatty acids, peroxide values of oxidation products, K232 and K270 values indicating the presence of conjugated dienes and trienes, as well as specific absorption bands of fatty acids, allowing these parameters to be accurately estimated. This method allows rapid and non-destructive assessment of the quality of EVOO, thus becoming a valuable tool for manufacturers and consumers. Olive oil fraud detection was studied with NIR spectroscopy [294–296]. The study of Melendreras et al. [295] focused on developing an affordable NIR spectroscopic system for fraud detection in olive oil [295]. Various mixtures for analysis using different types of olive oils were prepared, including natural, extra virgin, and refined, as well as seed oil additives consisting of sesame, sunflower, and linseed oils. Calibration models built using PLSR were able to detect fraud with high accuracy. The research demonstrated the potential of this technology to provide a cost-effective and practical solution. The ripening stage of olives was another hot topic for NIR study [288, 290, 297–299]. In the study of El Riachy et al. [288], the ripening processes of olives were examined by analyzing the fatty acids and phenolic profiles of extra virgin olive oils obtained from olive varieties grown in Europe and Lebanon with the help of NIR spectroscopy [288]. Partial Least Squares Discriminant Analysis (PLS-DA) was used as the regression model. To determine the degree of ripening, the color of the olive skin was considered an indicator of ripeness. Olives were classified into various ripening stages according to the color of their skins, and using a formula, the ripening index was calculated by considering the distribution of olives according to these stages.

As a Mediterranean food ingredient, herbs (especially thyme) were studied. They generally explore the factors that influence spectrum development, phase and concentration impacts, essential oil components, authenticity, and PLS regression properties through the simulation of herb's NIR spectra [300–305]. NIR spectroscopy represents an innovative approach that increases efficiency in the food industry while protecting consumer health and promoting sustainable use of food resources.

Table 2 summarizes the application of various novel technologies in the characterization of Mediterranean ingredients.

Challenges and Opportunities

The application of novel technologies for reformulating and characterizing Mediterranean ingredients presents various challenges and opportunities. One of the main challenges is the uneven energy distribution during microwave pasteurization, which can lead to hot and cold spots within the product, resulting in inadequate pasteurization or overprocessing. Addressing this requires design improvements and optimization at both pilot and industrial scales. Additionally, while microwave vacuum drying (VMD) offers superior moisture reduction and preservation of nutritional and sensory attributes, optimizing process parameters such as vacuum pressure and microwave power is critical to avoid nutrient degradation and maintain product quality. High-Pressure Homogenization (HPH) and High Hydrostatic Pressure (HHP) technologies present opportunities for enhancing Mediterranean foods' nutritional and sensory qualities by improving bioactive compounds' extraction and extending shelf life without significant thermal damage. However, the high costs associated with these technologies, as well as the need for specialized equipment and trained personnel, pose a significant challenges for widespread adoption. Cold Plasma Technology offers a non-thermal method to inactivate microorganisms and enzymes on food surfaces, maintaining nutritional and sensory properties. This technology's main challenge is scalability and the need to ensure consistent and effective treatment across different food matrices. In terms of characterization technologies, Nuclear Magnetic Resonance (NMR), Electron Paramagnetic Resonance (EPR), and Near Infrared (NIR) spectroscopy provide detailed insights into the molecular composition and quality of Mediterranean ingredients. These techniques offer rapid and non-destructive analysis, but their high cost and the requirement for advanced technical expertise can limit their application in routine food processing.

Table 2 Characterization of Mediterranean ingredients by novel technologies

Method	Samples	Application	References
NMR Spectroscopy and TD-NMR Relaxometry	Tomatoes	Examining tomato fruits and leaves by NMR metabolomics.	[205]
		Investigation on cell integrity of tomato seeds exposed to some treatments by NMR Relaxometry	[208]
		Selection of industrial tomatoes using TD-NMR data and computational classification methods.	[209]
	Olives and Olive Oils	Determining quality characteristics by NMR-based metabolic profiling of edible olives	[206]
		NMR studies on Italian PDO olive oils for characterization.	[210]
		^{1}H-NMR screening of fatty acid composition in edible oils.	[211]
		Detection of olive oil oxidation status during storage	[214]
	Herbs and Spices	Quality variation and standardization of black pepper (Piper nigrum)	[215]
		Geographical origin identification of Asian Red Pepper Powders using ^{1}H NMR Spectroscopy	[216]
		Determining Spice Authentication by NMR Spectroscopy and Chemometrics	[207]
	Plant Proteins	Examining hydration behavior of plant proteins via TD-NMR Relaxometry	[218–220, 328]
	Tomato-based Snack Bar	Examining water distribution on snack bars	[36]
	Tomato-based Sauce	Observing T_2 relaxation decay of water protons in different formulated sauces.	[222]
EPR spectroscopy	Tomatoes	Antioxidant activities of tomato lipid extracts	[254]
		Antioxidant capacity of tomato waste and assessment of the capability to scavenge hydroxyl and superoxide anion radicals	[255]
		Identification of free radicals after treatment of tomatoes with γ - radiation	[232]
		Identification of metal ions an9d determination of redox state and concentration manganese in tomato plant	[227]
	Spinach leaves	Identification of presence of Fe^{3+} and Mn^{2+} ions and determination rhombic symmetry of Fe^{3+} ions and divalent state of Mn^{2+} ions	[228]
	Olives and Olive Oils	Evaluation on the oxidative stability	[329]
		Effect of herbal extracts on oxidative stability and nutritional value of edible oils	[248]
	Fruits	Identification of free radicals after gamma irradiation treatment in fruit	[231]
	Herbs and Spices	Determination of free radicals generated by γ-irradiation and effect on antioxidant content	[231]
		Antioxidant activity after use of HVED in green extractions of bioactives from oregano leaves	[252]
		Antioxidant activity after use of HVED for recovery of bioactive compounds from Dalmatian sage	[251]
	Oat and Barley Bran	Antioxidative activity after ultrasound assisted modification of oat and barley bran	[250]
	Sardine (*Sardina pilchardus*)	Effect of the gamma radiation on antioxidant parameters during storage at two different temperatures in sardine	[253]

Table 2 (continued)

Method	Samples	Application	References
NIR Spectroscopy	Tomato	Determination of lycopene, soluble solids content (SSC), ripeness, taste-related compounds, pesticide residues	[243, 257, 259, 275, 281, 285]
		Quantitative analysis, predicting lycopene content, soluble solids content (SSC), taste-related compounds, Partial Least Squares Regression (PLSR)	[257, 273, 278, 330]
		Optimizing prediction models for lycopene content, Genetic Algorithm Partial Least Squares (GA-PLS)	[272]
		Analyzing sensory attributes and metabolite content, Principal Component Analysis (PCA)	[283]
		Classification and prediction of quality parameters, Support Vector Machines (SVM)	[268]
	Olive	Determination of ripening stage, fatty acid composition, phenolic profiles	[288, 297–299]
		Analyzing ripening stages based on skin color, Partial Least Squares Discriminant Analysis (PLS-DA)	[288]
		Analyzing fatty acid and phenolic profiles, Principal Component Analysis (PCA)	[288]
	Olive Oil	Quality control, determination of phenolic and antioxidant content, fatty acid composition, fraud detection	[286, 287, 291, 294, 295]
		Quality control, predicting acidity, peroxide value, phenolic profiles, Partial Least Squares Regression (PLSR)	[287, 288]
		Analyzing quality parameters like acidity, peroxide value, and phenolic content, Multivariate Regression Analysis	[263, 290]
		Discriminating based on fatty acid profiles and phenolic content, Principal Component Analysis (PCA)	[288]
	Thyme and Herbs	Quality control, determination of essential oil components, authenticity	[300–302]
		Analyzing essential oil components, Multivariate Regression Analysis	
		Classifying based on essential oil profiles, Principal Component Analysis (PCA)	

Despite these challenges, the opportunities presented by these novel technologies are significant. They offer the potential to enhance food quality, safety and sustainability. For instance, VMD and freeze drying can produce high-quality dried products with extended shelf life and preserved nutritional values. Technologies like PEF and HPH can improve the functional properties of food ingredients, making them more appealing to health-conscious consumers.

Moreover, integrating these technologies with traditional Mediterranean ingredients can lead to innovative food products that meet consumer demand for healthy, high-quality foods. Future research should optimize these technologies, reduce costs, and improve scalability to fully exploit their potential in the food industry.

Future Perspectives

The future of Mediterranean food processing looks promising with the adoption of novel technologies and innovative approaches such as nanotechnology, 3D food printing and biotechnological innovations, which hold significant potential for enhancing Mediterranean food products. Nanotechnology can facilitate the improved delivery of nutrients and bioactive compounds, thereby augmenting these foods' health benefits and disease prevention capabilities. The advent of 3D food printing offers the possibility of producing customized and aesthetically appealing food products that cater to individual dietary requirements and preferences while preserving the traditional flavors and textures of Mediterranean cuisine. Biotechnological innovations, including gene editing and advanced fermentation techniques, can enhance Mediterranean ingredients' nutritional profile and shelf life. These technologies also support the development of new food varieties with increased resilience to climate change and environmental stresses, ensuring a consistent and sustainable supply of high-quality Mediterranean food. By integrating these advanced technologies, the Mediterranean food industry can continue to innovate and provide consumers with nutritious, safe and sustainable food options. Future research should also focus on the sustainable cultivation and processing of Mediterranean ingredients. Exploring agroecological practices, such as vertical farming and precision agriculture, can enhance the yield and quality of crops like olives, tomatoes, and legumes while minimizing environmental impact. Developing alternative protein sources, such as lab-grown meat, plant-based sources and insect-based proteins, can complement traditional Mediterranean foods, offering sustainable and nutritious options. Incorporating functional ingredients, such as probiotics, prebiotics and bioactive compounds, into Mediterranean food products can enhance their health benefits and meet the evolving needs of health-conscious consumers. By embracing these innovative approaches and technologies, the Mediterranean diet can continue evolving, offering a healthy, sustainable, and enjoyable nutritional model for future generations.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflicts of Interest The authors declare no competing interests.

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