Review

Mediterranean Diet as a Nutraceutical and Sustainable Model for Health and Environmental Wellbeing

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Review

Mediterranean Diet as a Nutraceutical and Sustainable Model for Health and Environmental Wellbeing

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Abstract: The Mediterranean Diet (MD) has emerged as a comprehensive model for promoting human health and environmental sustainability. Rooted in a rich cultural and gastronomic heritage, the MD extends beyond nutritional adequacy, offering substantial nutraceutical benefits attributed to its high content of bioactive compounds such as polyphenols, carotenoids, omega-3 fatty acids, and phytosterols. These compounds contribute to the prevention and management of chronic non-communicable diseases through antioxidant, anti-inflammatory, cardioprotective, and neuroprotective mechanisms. Simultaneously, the MD aligns with sustainable food system principles, characterised by a predominantly plant-based composition, seasonal and local food sourcing, reduced reliance on animal-derived products, and minimal food waste. This dietary pattern has been associated with a significantly lower ecological footprint compared to Western diets, thus supporting broader environmental goals. This paper reviews the historical evolution, nutritional profile, bioactive composition, and epidemiological evidence supporting the MD, and proposes a reconceptualization of the traditional MD pyramid to emphasise its functional food components. Ultimately, the MD stands as a scientifically grounded, culturally embedded, and ecologically viable approach to foster both individual and planetary wellbeing.

Keywords: sustainable nutrition; bioactive compounds; food systems; food waste reduction; chronic diseases

1. Food: More than Nutrients

The provision of energy and essential nutrients is fundamental to the survival of all living organisms. In humans, these critical elements are acquired through dietary intake. The early ancestors of Homo sapiens undertook extensive journeys to gather berries, hunt, or fish as their primary source of food [1]. Over time, with domestication, humans began to engage in agriculture and animal husbandry, rather than relying solely on foraging for food [1,2]. This major shift marked the end of the nomadic lifestyle and facilitated the establishment of small settlements, which gradually expanded into complex societies and urban centers [2].

As civilisations evolved, the role of food went beyond its primary function of nourishment. It became a cultural and social phenomenon, deeply connected with human history and traditions [3-

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5]. The act of eating was transformed into a sensory experience, eventually giving rise to the early conceptualisation of gastronomy [3-5]. Culinary practices of different regions evolved based on locally available ingredients, climatic conditions, and historical influences, leading to the development of diverse gastronomic traditions [5,6].

In the 21st century, food remains a cornerstone of human survival, providing the necessary energy and nutrients required for physiological processes and cellular function [5]. Beyond its biological importance, food also promotes social cohesion, with meals serving as central events for family gatherings and communal interactions. Nevertheless, despite these enduring roles, traditional dietary patterns have undergone significant transformation, giving way to more processed foods, mass production systems, and a growing reliance on industrialised food chains. The cultural significance of food is further emphasised by its role in festivals, religious rituals, and national identities [5,6]. In Portugal, although there is no official total number, it is possible to identify at least 30 distinct gastronomic events held throughout the year of 2024, ranging from regional festivals to major national celebrations. This regional differentiation in culinary habits has given rise to distinct dietary patterns, that influence local and global food chains and economies [7,8].

Moreover, in addition to its nutritional and cultural significance, food contributes to the maintenance of health and prevents diseases [8-10]. Specific dietary interventions have been associated with weight management, metabolic regulation, and a reduced incidence of chronic diseases such as cardiovascular disorders, diabetes, and neurodegenerative diseases [8-10]. This is largely due to the presence of bioactive compounds in food, commonly referred to as nutraceuticals, which exhibit properties such as antimicrobial, anti-inflammatory, and antioxidant activities [10]. The exploration of functional foods and personalised nutrition became a focus in scientific research, highlighting the potential of dietary modifications to improve overall health and longevity [11,12].

2. Dietary Choices and Sustainability

Dietary choices play a crucial role in tackling food waste [13-15]. Local consumption can significantly reduce the energy used in transport and storage processes [15]. Currently, food waste before reaching consumers represents one of the most significant global challenges. Millions of tonnes of food are wasted each year, as illustrated in Figure 1. This trend is increasing due to a combination of inefficient production practices and population growth [13,14]. Addressing this problem requires the development of sustainable strategies to effectively mitigate its effects as it spans the entire food life cycle, from harvesting and production to distribution and consumption [13,14]. Therefore, it is crucial to develop and implement methods to reuse what is currently considered waste [14]. From a scientific perspective, food waste is one of the most critical areas of concern [14]. New strategies to reduce it are continuously being developed, making sustainable development a central focus in food science and related disciplines [13-15]. For instance, the implementation of smart packaging technologies - designed to monitor food freshness and extend shelf life - has emerged as a promising approach to minimise waste across the supply chain. Additionally, the valorisation of food by-products, such as using fruit peels or spent grains for the development of functional ingredients, is gaining traction as a circular economy measure. Furthermore, artificial intelligence and machine learning algorithms are being integrated into inventory and supply chain management systems to optimise purchasing, storage, and distribution, thereby reducing unnecessary surplus and spoilage [13-15].

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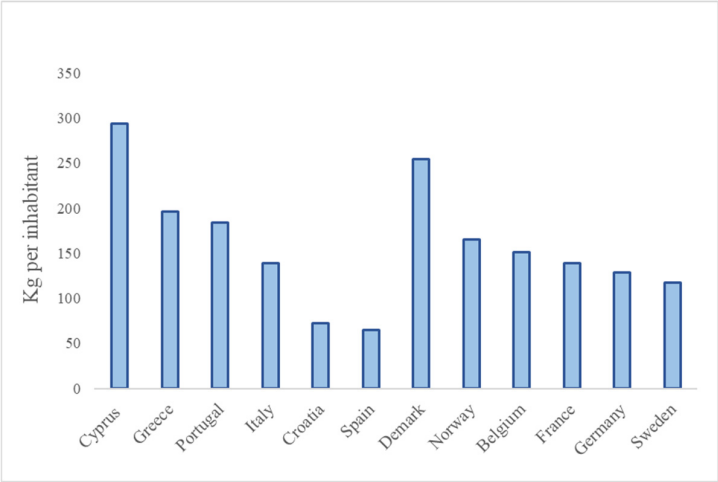

Figure 1. Food waste in the year 2022 in some European countries. Several kilograms of food are wasted annually per capita before reaching consumers, resulting in substantial quantities of wasted food at the national level. Portugal ranks as the fourth highest country in terms of food waste [14,15]. Adapted from [16].

Cyprus stands out as the country with the highest per capita food waste (approximately 295 kg per person), followed by Denmark and Greece. These results are particularly noteworthy in the European context, especially considering that some of these countries belong to the Mediterranean region, traditionally associated with more sustainable food practices. Portugal ranks fourth, with approximately 186 kg per person, indicating a concerning level of food waste, above the European average (≈131 kg per person) [15]. This position suggests that, despite the cultural appreciation of food and the Mediterranean diet (MD), significant challenges remain in the efficient management of food throughout the supply chain. In contrast, countries such as Spain and Croatia report significantly lower levels of per capita food waste, below 80 kg, which may reflect more effective national strategies or different consumption habits. Overall, Figure 1 highlights that even among countries with similar food traditions (such as Mediterranean nations), there is considerable disparity in waste levels. This underscores the importance of effective public policies, food education, and technological innovation to mitigate this environmental and socio-economical issue.

In addition to its economic and social impact, food waste also exacerbates the environmental issues associated with food production. Producing food that ultimately goes to waste involves an unnecessary use of natural resources and increases the ecological footprint of the agri-food sector. Food production remains one of the most significant contributors to environmental pollution, mainly due to the extensive release of greenhouse gases and the substantial consumption of water and energy resources [17,18]. Agricultural activities, especially intensive farming, exacerbate climate change by producing large amounts of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [19,20]. In addition, large-scale production relies heavily on agrochemicals, such as pesticides and synthetic fertilisers, which not only degrade soil quality but also contaminate aquatic ecosystems, leading to biodiversity loss and the disruption of aquatic food chains [21,22].

The export and distribution of food involve high energy expenditures for transportation, refrigeration, and packaging, all of which contribute to fossil fuel consumption and increased emissions [23]. In addition, inefficient logistics and inadequate storage conditions result in significant food losses before products even reach consumers [24,25].

Addressing these challenges requires the urgent implementation of innovative and sustainable strategies aimed at restructuring food production systems. The development and adoption of environmentally friendly agricultural techniques, such as precision and organic farming or regenerative agriculture, is essential to reduce dependence on chemical inputs and improve resource efficiency [26]. For example, precision farming uses data and technology to optimise crop yields while minimising resource use, thereby reducing waste and environmental impact. Similarly, regenerative

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agriculture focuses on rebuilding soil health and enhancing biodiversity, which can lead to more resilient food systems and reduced environmental degradation. Integrating circular economy principles into the food chain - such as recycling food waste into bioenergy or compost - also plays a crucial role in reducing pollution and promoting sustainability [27,28].

In addition, public engagement and education are key to promote more responsible consumption habits. To raise awareness about reducing food waste, promote sustainable dietary choices, and encourage local food sourcing can collectively contribute to minimise environmental impacts [29,30]. The implementation of policies that support sustainable agriculture, improve the efficiency of food distribution and encourage responsible consumer behaviour will further strengthen efforts to reduce pollution and food waste on a global scale [31].

3. Diet as a Major Factor in Healthier Living

A diet should be based on principles that enable individuals to improve their health in a less invasive way than surgical procedures or pharmacological interventions [32]. Consequently, a well-structured and nutritionally balanced diet can improve quality of life by reducing the risk of non-communicable diseases (NCDs) and promoting physiological well-being [32].

Adherence to the MD is consistently associated with a reduced incidence of NCDs, which represent a major global health concern. NCDs are chronic conditions not transmitted through infectious agents and are typically linked to modifiable behavioural risk factors such as poor diet, physical inactivity, and tobacco use [32]. These diseases include, but are not limited to, cardiovascular disease (CVD), cancer, chronic respiratory diseases, and type 2 diabetes mellitus [32,33]. Collectively, they account for the leading causes of morbidity and mortality worldwide, with NCDs responsible for approximately 41 million deaths annually equating to over 70% of total global mortality [32-34].

Typically, weight loss is a primary motivation for adopting a particular eating plan [3]. However, recent research has highlighted that diets go beyond weight management and provide additional health benefits through the intake of bioactive compounds present in certain foods. These compounds may confer nutraceutical advantages, including anti-inflammatory, antioxidant, and lipid-lowering effects [34,35]. For example, conditions such as CVD can be managed through a healthy and regulated diet, particularly one rich in fruits, vegetables, whole grains, and omega-3 fatty acids [32,33]. Adherence to dietary patterns such as the MD or the DASH (Dietary Approaches to Stop Hypertension) diet has been shown to reduce the incidence of coronary heart disease, stroke, and metabolic syndrome [36].

Planned dietary intake not only supports weight regulation but also contributes to the prevention and management of NCDs, thereby increasing healthy longevity and reducing healthcare burden [34,37,38]. The integration of dietary strategies as a preventive tool is increasingly recognised in public health policies and clinical practice guidelines worldwide.

Many doctors often recommend dietary changes to manage high blood pressure, a condition that raises the risk of stroke and heart attack, about 34% of men and 32% of women globally live with high blood pressure [39]. For example, bananas are rich in potassium - a mineral that helps control blood pressure by counteracting the effects of sodium and reducing vascular resistance [40]. Similarly, watermelon, which contains citrulline, an amino acid that promotes the endogenous production of nitric oxide, improves endothelial function by increasing arterial flexibility, thereby reducing elevated blood pressure levels [40,41]. Other functional foods, such as garlic, dark chocolate, and leafy vegetables, have been shown to have similar blood pressure-lowering effects via different biochemical mechanisms [42,43].

There are numerous examples of foods that can reduce and control medical conditions through mechanisms involving lipid regulation, glycaemic control, and immunomodulation. This has led to the development of evidence-based dietary guidelines and the formulation of various culturally adapted diets worldwide, aimed at both disease prevention and health promotion (Table 1).

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Table 1. Common diets [16,44]. Diets offer non-invasive health improvements compared to surgery or medication, improving quality of life and managing conditions such as cardiovascular disease through nutraceutical properties.

Diet	Acronym	Description
Dietary Approaches to Stop Hypertension	DASH	A dietary pattern designed to lower blood pressure, emphasising the intake of fruits, vegetables, whole grains, and low-fat dairy products, while limiting sodium, saturated fats, and added sugars.
Flexitarian Diet	FD	A predominantly plant-based diet that permits occasional consumption of meat and fish. It prioritises vegetables, legumes, and whole foods, promoting cardiovascular health and weight management.
Mediterranean Diet	MD	Based on traditional eating habits of Mediterranean countries, this diet is rich in olive oil, fruits, vegetables, whole grains, and fish. It is associated with reduced risk of chronic diseases.
Therapeutic Lifestyle Changes	TLC	A dietary strategy aimed at reducing LDL cholesterol. It includes foods high in soluble fibre, plant sterols, and unsaturated fats, and is often combined with regular physical activity.

The Nutraceutical Impact

In addition to essential nutrients, food often contains a wide range of bioactive compounds. These are naturally occurring chemical substances, primarily phytochemicals that are not essential for basic human nutrition yet may exert significant health-promoting effects [45,46]. Due to their pharmacologically relevant properties, such compounds are often referred to as nutraceuticals - a term derived from the combination of “nutrient” and “pharmaceutical” [46].

Among the various classes of bioactive compounds, those exhibiting antioxidant and anti-inflammatory properties have attracted considerable scientific interest. Antioxidants play a crucial role in mitigating oxidative stress, a pathological condition characterised by the accumulation of reactive oxygen species that damage cellular structures, including lipids, proteins, and DNA [47]. Chronic oxidative stress has been implicated in the pathogenesis of several NCDs, including cardiovascular disease, neurodegenerative disorders, and several types of cancer [47-49].

Dietary antioxidants such as polyphenols (e.g., flavonoids, phenolic acids), carotenoids (e.g., β-carotene, lycopene), and vitamins C and E, are widely distributed in fruits, vegetables, legumes, nuts, and seeds [50]. These compounds have been shown to be effective in reducing oxidative damage, improving endothelial function, and modulating lipid metabolism [50-52].

Similarly, bioactive compounds with anti-inflammatory activity are of particular interest in the context of chronic low-grade inflammation, which underlies many diseases including type 2 diabetes, rheumatoid arthritis, and inflammatory bowel disease [53]. Phytochemicals such as curcumin from turmeric, resveratrol from grapes, and sulforaphane from cruciferous vegetables help regulate inflammation by influencing key pathways [54,55].

Thus, the regular consumption of plant-based foods rich in such bioactive compounds may contribute to the prevention and management of chronic diseases by modulating oxidative and inflammatory processes at the molecular level.

4. Mediterranean Diet

The MD is recognised as making a significant contribution to improved health outcomes and enhanced quality of life, a view that is strongly supported by both the scientific community and the general population [56].

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The health benefits associated with the MD were first systematically recognised in the mid-20th century, mainly through comparative epidemiological studies [56-58]. During this period researchers observed that the inhabitants of the island of Crete had significantly higher longevity rates and lower incidences of chronic diseases compared to populations in North America [57,58]. This observation laid the foundation for a new field of nutritional science. The term "Mediterranean Diet" was subsequently coined by the American physiologist Ancel Keys, who played a pivotal role in highlighting the protective effect of Mediterranean dietary patterns against CVD [59]. His findings were based on longitudinal analyses, notably the Seven Countries Study, which demonstrated a significantly lower incidence of CVD and increased life expectancy among Mediterranean populations, largely due to their traditional dietary practices [56-60].

This study identified a strong correlation between dietary fat intake and CVD mortality. While a high total fat intake was typically associated with increased cardiovascular risk [56-60], populations living in the Mediterranean basin appeared to be a notable exception. Despite their relatively high fat consumption, these communities had some of the lowest CVD mortality rates in the world [61,62]. This paradox was explained by the predominant type of fat consumed - unsaturated fats, especially monounsaturated fats, derived mainly from extra virgin olive oil, often consumed unheated and in its natural state. Olive oil emerged as a central component of the MD, distinguishing it from Western dietary patterns that relied more heavily on saturated and trans fats [60-62].

In addition to the significant role of olive oil, the MD is characterised by a high intake of plant foods, including whole grains, legumes, fresh fruits, nuts, and a diverse array of vegetables [63]. Fish and seafood are also important, while the intake of red and processed meats, dairy products, eggs, potatoes, and added sugars tends to be moderate [60-63]. This composition reflects not only nutritional adequacy but also sustainable agricultural and culinary practices that have been maintained over generations in several Mediterranean countries [16,64].

Importantly, the MD is not limited to its nutritional aspects. It also encompasses a wide range of socio-cultural dimensions that together define it as a holistic lifestyle model. These include communal eating, culinary traditions passed down through generations, local food production, biodiversity, and seasonal food consumption [56,64]. Thus, MD is increasingly recognised not only as a diet, but also as an integrative cultural and social framework that promotes physical, environmental, and social well-being [56,65]. This is at the basis of the heterogeneity in dietary habits between different Mediterranean countries and even between different regions within the same [56-58,66].

4.1. Mediterranean Diet Pyramid

This diversity arises from a complex interplay of geographical, cultural, economic, and agricultural factors that influence local food availability, culinary traditions, and dietary customs [67]. Despite this variability, several core characteristics have been consistently identified in the literature that provide a general framework for what constitutes the MD [56,68].

These common features include the daily consumption of minimally processed or unrefined cereals, such as wholemeal bread, pasta, and rice; a high intake of both raw and cooked vegetables, which are rich in fibre, vitamins, and phytochemicals; and the predominant use of extra virgin olive oil as the main source of dietary fat [56,69]. Additionally, the MD includes the regular consumption of seasonal and locally grown fruits, which contribute significantly to daily antioxidant intake, and the habitual consumption of oily fish such as sardines, anchovies, and mackerel, which provide essential long-chain omega-3 polyunsaturated fatty acids [69,70]. Dairy products, mainly in the form of yoghurt and cheese, are consumed in moderation, while the intake of red meat and processed meat products is limited and sporadic [56,70].

To facilitate the practical implementation of this dietary model, a widely accepted tool has been developed in the form of the MD Pyramid, shown in Figure 2. This pyramid serves as a visual dietary guide, outlining recommended frequencies and portion sizes for different food groups, and incorporating lifestyle practices adapted to the realities of modern life [71-73]. It reflects the consensus of international experts based on the best available scientific evidence available and is specifically

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designed for adults aged 18 to 65 years [71-73]. The base of the pyramid includes foods that are recommended to be consumed daily and in larger amounts, such as vegetables, fruits, whole grains, legumes, nuts, and olive oil [71-73]. In contrast, foods positioned at the top of the pyramid - such as red meat, sweets and processed foods - should be consumed occasionally and in small portions [71-73].

Figure 2. Mediterranean diet pyramid. Schematic representation of the typical foods present in the Mediterranean diet as well as the regularity with which they should be consumed. It is also possible to observe the indication for sports practice that must be accompanied by this diet but also characteristics beyond it that accompany it such as coexistence and seasonality. Adapted from [72].

Beyond dietary recommendations, the pyramid also highlights the importance of regular physical activity, adequate hydration, and social and cultural practices related to food preparation and consumption [74]. These include shared meals, culinary knowledge transmission, and mindful eating, all of which are integral components of the Mediterranean lifestyle [72]. Notably, the flexible nature of the MD allows for the inclusion of individual preferences and regional variations, thereby enhancing adherence and long-term sustainability [70-74].

Moreover, the seasonal nature of the MD, whereby foods are harvested and consumed in accordance with their natural growing cycles, contributes to dietary variety throughout the year [75]. This practice supports ecological sustainability by reducing the environmental impact associated with intensive food production and long-distance transportation, thereby aligning the MD with broader goals of environmental conservation and sustainable development [75].

4.2. Mediterranean Diet Health Benefits

Extensive epidemiological and clinical evidence has demonstrated a strong inverse association between adherence to the MD and overall mortality risk, indicating increased longevity among adherents [76-79]. The MD has been shown to significantly reduce the incidence of specific NCDs, particularly CVD and type 2 diabetes mellitus [77-80]. Figure 3 presents an overview of selected diseases that can be mitigated through sustained adherence to the MD. It is estimated that up to 90% of type 2 diabetes mellitus cases and approximately 70% of cerebrovascular accidents (strokes) could be prevented through adherence to the MD when combined with regular physical activity [81].

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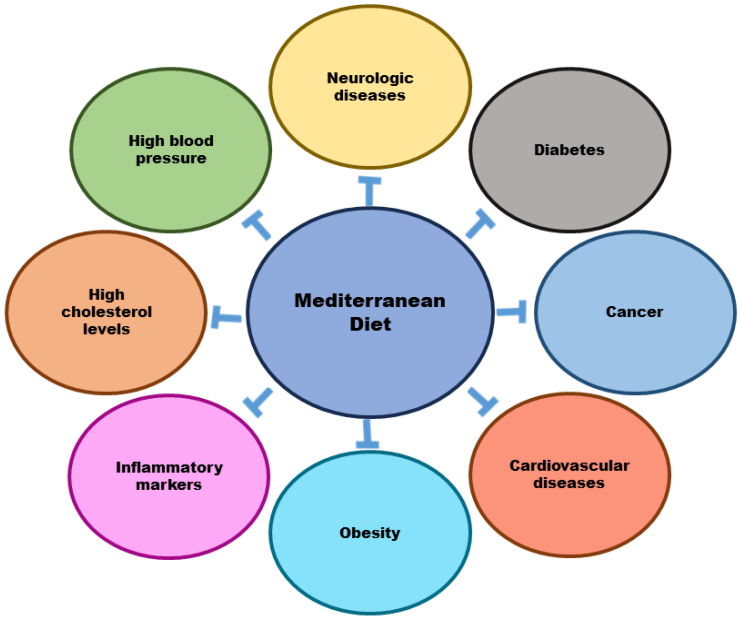

Figure 3. Health benefits of the Mediterranean diet. The consumption of this diet can lead to a reduction in the occurrence of certain pathologies. Adapted from [16].

The extensive health benefits of the MD are supported by numerous large-scale studies. The PREDIMED (Prevención con Dieta Mediterránea) trial was a landmark, multicentre, long-term randomised controlled trial, conducted in Spain and enrolled over 7,000 individuals aged 55 to 80 years, all at high cardiovascular risk [82,83]. The main results showed that MD significantly reduced the incidence of major cardiovascular events in both diabetic and non-diabetic populations.

In addition to cardiovascular outcomes, adherence to the MD has been associated with significant improvements in glycaemic control [84]. Clinical trials have reported that individuals following the MD, especially those who are obese and non-diabetic, experience improved insulin sensitivity and better glucose tolerance compared to those on control or low-fat diets [84,85]. Furthermore, key components of the MD, such as extra virgin olive oil, contribute to these benefits by reducing systemic inflammation, oxidative stress, and increasing plasma antioxidant capacity [83-85].

4.3. Family of Compounds with Bioactive Potential Associated with the Mediterranean Diet

Polyphenols represent one of the most significant classes of bioactive compounds in the MD, with high concentrations found in extra virgin olive oil, red wine, fruits, vegetables, legumes and herbs. Among these, hydroxytyrosol and oleuropein, mainly found in olives and olive oil, have demonstrated powerful antioxidant properties, which induce the expression of endogenous antioxidant enzymes such as superoxide dismutase and glutathione peroxidase [86]. Resveratrol, a stilbene abundant in red wine, contributes to cellular homeostasis by modulating pathways involved in mitochondrial biogenesis and energy metabolism, particularly via the SIRT1 and AMPK pathways [87]. It also downregulates pro-inflammatory cytokines through inhibition of NF-κB, thereby reducing systemic inflammation - a major risk factor for cardiovascular and metabolic disease. Other polyphenols, including flavonoids such as quercetin and kaempferol, exert anti-inflammatory and anti-atherogenic effects by modulating mitogen-activated protein kinases and reducing the expression of adhesion molecules such as VCAM-1 and ICAM-1 [88].

Another prominent group of MD bioactive compounds are carotenoids, a class of lipid-soluble pigments responsible for the vibrant colours of many fruits and vegetables. Lycopene, highly concentrated in tomatoes and particularly bioavailable when cooked, has potent singlet oxygen-

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scavenging properties and has been associated with reduced risk of prostate cancer and cardiovascular disease through the modulation of oxidative stress and inflammatory markers such as CRP and IL-6 [89]. β-carotene, found in carrots and pumpkins, acts as a precursor to vitamin A and supports immune function and epithelial integrity, while lutein and zeaxanthin contribute to ocular health by protecting the retina from light-induced oxidative damage [90].

Phytosterols, including β-sitosterol and campesterol, are naturally occurring plant sterols structurally similar to cholesterol, found in legumes, nuts and seeds. These compounds competitively inhibit cholesterol absorption in the intestinal lumen, resulting in reduced plasma LDL-cholesterol levels [91]. In addition to their hypocholesterolaemia effect, phytosterols may also exhibit anti-inflammatory properties by influencing immune cell activity and suppressing the synthesis of inflammatory mediators.

Though consumed in moderate amounts in the MD, omega-3 polyunsaturated fatty acids, particularly eicosapentaenoic acid and docosahexaenoic acid from oily fish such as sardines and mackerel, are central to its nutraceutical profile. These fatty acids reduce the production of pro-inflammatory eicosanoids derived from arachidonic acid and promote the biosynthesis of specialised pro-resolvers, which actively contribute to the resolution of inflammation [92]. Docosahexaenoic acid also plays a key role in neuronal membrane fluidity, synaptogenesis and neuroprotection, and is associated with improved cognitive performance and reduced risk of neurodegenerative disorders [93].

Organic sulphur compounds, found in allium vegetables such as garlic and onions, provide additional bioactive complexity to the MD. Allicin, diallyl disulphide and S-allyl cysteine, among others, have demonstrated antioxidant, antimicrobial and cardioprotective properties. These compounds enhance endogenous detoxification mechanisms by inducing phase II enzymes, inhibit the activation of carcinogens, and improve endothelial function by increasing nitric oxide bioavailability [94].

Finally, dietary fibre plays an indispensable role in the diet's nutraceutical capacity. The fermentation of soluble fibres by colonic microbiota produces short-chain fatty acids (SCFAs) such as butyrate, acetate and propionate, which exert multiple systemic effects. SCFAs modulate immune responses through G-protein-coupled receptors, improve insulin sensitivity, maintain intestinal barrier integrity and exert anti-inflammatory and anti-tumorigenic effects [95]. Butyrate, in particular, functions as a histone deacetylase inhibitor, influencing gene expression and contributing to the regulation of inflammatory pathways [96].

Considering this, we decided to reinterpret the MD pyramid from a different perspective (Figure 4). By focusing on its bioactive compounds, it is possible to construct a pyramid that links these components to specific foods. The MD contains a rich spectrum of bioactive compounds that collectively influence key physiological pathways involved in the prevention of chronic diseases. These compounds - through their antioxidant, anti-inflammatory, lipid-lowering, glycaemic-regulating, and neuroprotective properties - underpin the nutraceutical potential of the diet. Their synergistic activity, enhanced by traditional culinary methods and the emphasis on whole foods, strengthens their beneficial effects. This highlights the MD as not just a diet, but as a holistic nutritional framework designed to promote long-term health and longevity.

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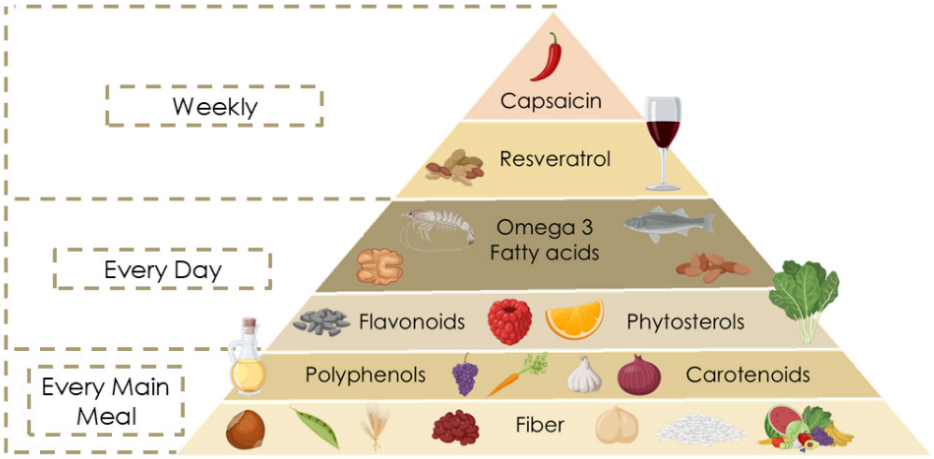

Figure 4. Most Predominant Families of Compounds in the Mediterranean Diet Represented in a Pyramid with Key Food Sources and Consumption Frequency.

Restructuring the traditional MD pyramid to emphasise key bioactives - such as polyphenols, flavonoids, carotenoids, phytosterols, and omega-3 fatty acids - offers a more functional and mechanistic perspective on dietary recommendations. This bioactive-focused model underscores not only the consumption of specific food groups but also the health-promoting molecules they contain, which are known to exert antioxidant, anti-inflammatory, cardioprotective, and neuroprotective effects. By incorporating frequency-based guidance (e.g., daily or weekly intake) aligned with these compounds' bio efficacy, the updated pyramid provides a scientifically grounded framework for personalised nutrition and preventive health strategies. This conceptual pyramid illustrates the MD through its major bioactive compounds, associating each class with representative food sources. From the base to the apex, the structure reflects the relative abundance and fundamental role of each group: dietary fibre, polyphenols, carotenoids, flavonoids, phytosterols, omega-3 fatty acids, resveratrol, and capsaicin. These compounds, naturally occurring in whole foods characteristic of the Mediterranean dietary pattern, collectively contribute to the diet's recognised health benefits through antioxidant, anti-inflammatory, metabolic, and neuroprotective mechanisms.

The restructuring of the Mediterranean diet pyramid to emphasise bioactive compounds reveals the multifaceted functional role of this dietary pattern. Beyond its well-established cardioprotective effects, the diet demonstrates potent prebiotic properties, primarily due to its richness in dietary fibre, polyphenols, and flavonoids, which promote beneficial shifts in gut microbiota composition. Additionally, bioactives such as carotenoids, omega-3 fatty acids, and resveratrol contribute to anti-inflammatory, antioxidant, and immunomodulatory actions, supporting the prevention of chronic diseases including metabolic syndrome, cardiovascular disorders, and neurodegenerative conditions. This refined model underscores the MD as not only a cultural and nutritional framework but also a scientifically grounded therapeutic strategy for long-term health promotion and disease prevention.

4.4. Environmental Sustainability of the Mediterranean Diet: A Model for Eco-Friendly Nutrition

Beyond its well-documented clinical and nutritional benefits, the MD also offers significant environmental advantages. Growing evidence suggests that the MD has a significantly lower environmental footprint than other dietary patterns, particularly Western-style diets [97-100]. Characterised by a high intake of plant-based foods and minimal consumption of animal products, the MD contributes to reduced greenhouse gas emissions and a lower overall water footprint [98-102]. One of the critical ecological strengths of the MD lies in its inherent seasonality. The emphasis on seasonal products encourages more sustainable agricultural practices, reduces the energy required for food production and storage, and lowers the associated environmental costs [102,103]. Moreover,

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the preference for local and regional food sources in MD adherent populations minimise the need for long-distance transport. This reduction in food miles not only decreases fossil fuel consumption and associated emissions but also helps stabilise food prices and support local economies [102-104].

Another notable dimension of the MD sustainability is its association with reduced food waste. Traditional Mediterranean food culture, which includes practices such as using leftovers, preserving seasonal products, and prioritising fresh ingredients, is closely aligned with modern zero waste principles [105]. Data presented in Figure 5 highlights a concerning rise in food waste across Europe, with northern European countries exhibiting higher levels of waste compared to their southern counterparts. Notably, the waste illustrated in this figure refers to losses occurring along the supply chain prior to reaching the end consumer. This discrepancy can be attributed to multiple factors, including differing economic conditions, cultural attitudes towards food, and dietary habits [102-106].

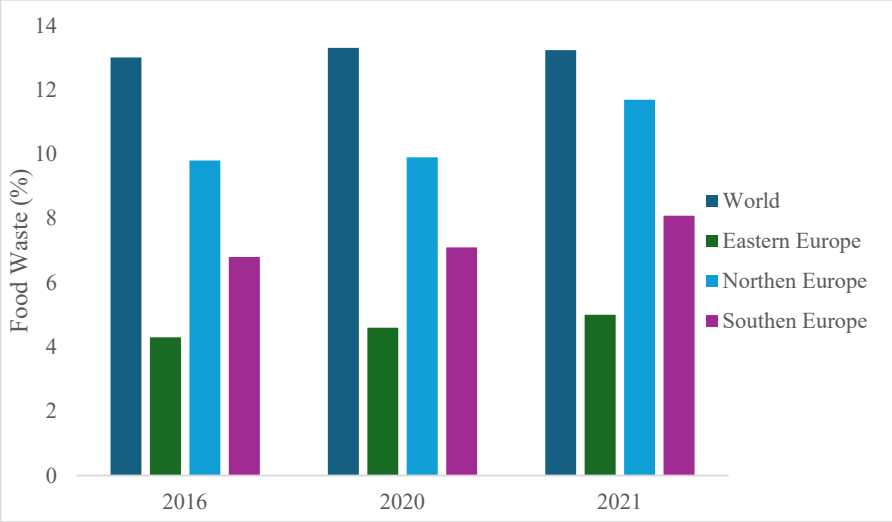

Figure 5. Food loss in the years 2016, 2020 and 2021 (most recent data). Several kilograms are wasted per year per inhabitant before reaching consumers, which ultimately leads to tons of wasted food in each country. Adapted from [16]. It is estimated that approximately 13% of food is lost annually during post-harvest, storage, transport, and processing stages, resulting in millions of tonnes of food wasted globally.

The MD emerges not only as a model of health-promoting nutrition but also as a benchmark for sustainable dietary practices. As global food systems face increasing environmental pressures, adopting the principles of the MD could play a crucial role in promoting both human and planetary health.

5. Conclusions

The MD stands out as a dietary model that goes beyond its nutritional value, serving simultaneously as a tool for public health promotion and an example of environmental sustainability. Its richness in bioactive compounds with nutraceutical properties positions it as a key strategy in the prevention of chronic NCDs, through antioxidant, anti-inflammatory, and cardioprotective mechanisms. Furthermore, by prioritizing local, seasonal, and plant-based foods, it encourages sustainable agricultural practices and reduces food waste, thereby lowering the environmental footprint of the food system. This integrated approach, combining culinary tradition, nutritional science, and sustainability principles, elevates the MD to more than just a dietary pattern; it is a cultural and ecological heritage with the potential to positively impact both human and planetary health.

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Abbreviations

The following abbreviations are used in this manuscript:

MD	Mediterranean Diet
NCDs	Non communicable Diseases
CVD	Cardiovascular Diseases
SCFAs	Short-Chain Fatty Acids

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