Review

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Review

Mediterranean Diet in the Era of Climate Change: A Reference Diet for Human and Planetary Health

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Abstract: The climate change constitutes nowadays an enormous global threat for human health and environmental sustainability. The expanding world population and the increased global needs for food production have an important negative impact upon environment. Diet can link human health with environmental sustainability. Food production systems are closely related to anthropogenic greenhouse gas emissions and the aggravation of climate change, and current western type, animal-based, dietary patterns may lead to adverse environmental footprints. In the present narrative review, we address the interconnection of the Mediterranean diet (MD) with climate change and sustainability. MD is a highly recommended dietary intervention for the prevention and management of various endocrine and cardiometabolic diseases. Beyond its evidence-based, health-promoting effects, it also has beneficial environmental impact, reducing greenhouse gas emissions and enhancing biodiversity, food security and sustainability. Based on the evidence reviewed herein, MD should be incorporated within the framework of a "One Health" model, which involves the improvement not only of human health but also of planetary health and food system sustainability. Our review aims to provide a stimulus for health professionals to strongly recommend the implementation of MD under the current pressure of climate change, despite all barriers, targeting both human health preservation and the planetary well-being.

Keywords: Mediterranean diet; plant-based dietary patterns; climate change; sustainability; sustainable food systems; environment; greenhouse gas emissions

1. Introduction

In the ancient Greek times, Hippocrates was one of the first scientists who emphasized the importance of the interconnection between environmental conditions and certain types of diseases. He believed in the need of living in harmony with nature in order to maintain a good physical and mental health. According to Hippocrates, "Human health does not depend solely on physiology, but is also in close interaction with the external environment in which humans live, as it may significantly affect their proportions in the human body". In order to create a strong bond between humans and their environment, it is crucial to ensure a healthy safe diet and sufficient food resources for the constantly growing population [1].

The globally increased needs for food consumption play a fundamental role for the detrimental effects of climate change (CC). CC has been related to the reduction of biodiversity, the depletion of natural resources, and other adverse environmental impacts induced by the modern households [2]. It has been predicted that the increasingly harsh phenomena of global CC will gradually decrease both food security and diet quality, and will reduce water availability, ecosystem biodiversity and the nutritional value of foods. This will occur mainly due to the impoverishment of the soil, combined with the expected continuous increase of food request [3]. CC will ultimately affect the sustainability

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of food production systems by directly impacting crop yields, nutrient composition and bioavailability, leading vulnerable populations to malnourishment and undernutrition [4]. These ominous data highlight the urgent need to take measures to improve food system sustainability. Relevant studies have shown that food production systems account for up to 37% of anthropogenic greenhouse gas emissions (GHG) and 70% of freshwater use on a global scale [5,6]. The shift of the present dietary habits to more sustainable food systems has been proposed as an effective measure to reach global GHG emission reduction targets and contribute to the decarbonization of the European continent by the year 2050 [7].

A large body of solid scientific evidence strongly recommends the adoption of plant-based dietary patterns for both human and planetary health promotion [8,9]. It has been consistently shown that plant-based dietary patterns contribute to a healthier diet and to reduction of environmental impacts through lower GHG emissions and resource consumption [10]. A systematic review of meta-analyses of prospective studies which examined the association between the incidence of cardiovascular disease (CVD) and certain types of food groups, concluded that a dietary pattern oriented more on plant-derived foods is able to optimize CVD prevention [5]. Unfortunately, within the last 50 years, a dramatic change of dietary patterns has been observed, mainly characterized by an increased consumption of animal-based products and an over-consumption of high-fat energy-dense foods, leading to poor population health and negative environmental footprints [11]. Dietary patterns of poor quality represent the main risk factor for the development of non-communicable diet-related diseases, such as obesity, type 2 diabetes mellitus (T2DM), malignancies and CVD, accounting for approximately 41 million deaths each year globally [5,12].

Several studies and reviews acknowledge the Mediterranean diet (MD), a world-renowned healthy diet, as a reference diet in terms of sustainability and environmental impact [8,13–16]. The Mediterranean dietary pattern (MDP) as a whole may serve as an outstanding model of a sustainable and environment-friendly nutritional system. In addition to its well-established beneficial effects on human health and chronic disease prevention and management, the MDP fulfils all those qualitative requirements which make it a sustainable diet with an essential role for CC and environmental stability [8,17,18]. The aim of the present narrative review was to provide a concise update of the ecological implications of the MDP, emphasizing its potential to promote food system sustainability and mitigate the negative consequences of global CC, in addition to its well-documented health-promoting beneficial effects in chronic disease prevention and treatment. In this review, we underline the importance of MD as an eco-friendly dietary pattern with optimal human and environmental impact, we discuss potential barriers to its widespread adoption, and we emphasize the urgent need to implement a dietary pattern with these qualitative characteristics for individual health and environmental protection, which are strongly interconnected.

2. Methods of Literature Search and Review Criteria

For the preparation of the present review, we applied the following search terms "Mediterranean diet", "plant-based dietary patterns", "sustainability", "climate change", "environmental footprints", "greenhouse gas emissions," "environmental impact", "sustainable diets", "sustainable food systems" and "endocrine aspects", in all possible combinations, in order to retrieve the available scientific literature data from PubMed, Medline and Google Scholar electronic databases from inception until June 2024. We included papers written in English language that involved reviews, epidemiological reports, observational and environmental studies, and additional references were retrieved from reviewing the references cited in the original articles.

3. The Definition of Sustainability and Sustainable Food Systems

The term "sustainability" has been defined by the World Commission on Environment and Development as "the development that meets the needs of the present, without compromising the ability of future generations to meet their own needs" [19]. Sustainable dietary patterns are characterized by the following three specific features: 1) low environmental impact of food production, 2) high food security, and 3) contribution to a healthier life. Sustainable diets respect and

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protect the biodiversity of ecosystems, they optimize natural and human resources, and they are easily accessible, economically affordable and socioculturally acceptable [20,21]. In addition, a sustainable diet should be nutritionally balanced, healthy and safe [22–24]. The principal target of a sustainable dietary pattern should be to keep GHG emissions within the planetary limits of sustainability and prevent serious health problems through a healthy dietary plan [25]. Food and Agriculture Organization (FAO) and World Health Organization (WHO) clearly suggest that healthy and sustainable diets should provide adequate, safe and nutrient-rich food for all [26].

Due to the higher sustainability of plant-based foods in relation to foods of animal origin, it is suggested that a dietary plan with a higher proportion of these foods can have a drastic global environmental impact [27,28]. Omnivorous dietary patterns, reflecting the western-type dietary habits prevalent in most countries, have a clearly negative environmental impact, mainly driven by the increased amount and frequency of animal food consumption [29,30]. More specifically, studies have shown that even a moderate consumption of animal food products (meat and dairy products) may be detrimental for environmental ecosystems and human health [2,31]. Based on these data, Pieper et al. concluded that a gradually reduced reliance of countries on animal food products could represent one of the most effective measures for the restriction of diet-related environmental impact [32].

According to statistical figures from WHO, over 800 million people of the global population are currently undernourished, while in the same time, more than two billion are overweight/obese and display various micronutrient deficiencies [13]. Several health-promoting international organizations such as "The United Nations (UN) Decade of Action on Nutrition (2016-2025)", FAO and WHO, are actively engaged in promoting sustainable food systems that contribute to healthy dietary patterns, all of them being in line with UN Sustainable Development Goals (SDGs) [33,34].

4. The Relationship of Sustainability with Climate Change

It has become more than evident that human activities can alter environmental aspects and transform the physical and biogeochemical environment all over the world [35]. Berry et al. have listed numerous activities with high environmental impact including urbanization, reclamation of the land, deforestation, intensification of the agriculture, waste production, fresh water extraction, and over-exploitation of fisheries [8]. All these activities have aggravating effects on vital environmental parameters such as climate variability, global warming and atmospheric composition, nitrogen cycling, water quality and quantity, land cover, sea levels and biodiversity both on land and in the sea [8]. CC has been associated with biodiversity loss, food insecurity, unpredicted weather phenomena and harmful health consequences [18].

The Mediterranean region is considered to be one of the most affected regions in terms of CC, presenting higher temperature levels in the summer, massive and devastating forest fires, reduced biodiversity, land degradation and water scarcity. During the last decades, all these phenomena have been combined with a dramatic alteration of nutritional quality and reduced adherence to the traditional Mediterranean diet patterns [36–38]. Of note, Mediterranean region is a CC hotspot and one of the most water-scarce regions in the world. Due to the CC impact, the whole region presents serious problems with vegetation and hydrologic cycle [39].

Under the pressure of the life-threatening effects of CC, the European Union (EU) has set the target to achieve the seventeen (17) SDGs of the UN Agenda for Sustainable Development by the year 2030 [40]. The aforementioned SDGs were adopted in 2015 by the 193 member states of the UN, and they are focused on optimizing food production, food distribution and preservation of natural resources, in order to mitigate the adverse CC consequences. Among the 17 goals, the goal number 12, defined as "responsible production and consumption", refers among other things to eating habits and to the production, processing and consumption of food, in a process ensuring food system sustainability [40,41].

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5. Defining the Characteristics of an Environment-Friendly Dietary Pattern

CC can affect diet through effects on the agricultural production. Factors such as high temperatures, increased frequency of droughts, salinization of agricultural land and aquifers, changes in the frequency and quantity of rainfall, greater frequency of heat waves and rising levels of the sea have a deleterious effect on agricultural production [42]. According to FAO's report, "it will become more difficult and more expensive to grow, raise animals, managing forests and fish in the same places as before" [43]. For this reason, a shift of the contemporary unhealthy diet, being primarily based on animal-derived foods, towards a more plant-based dietary pattern, is expected to exert beneficial effects on the environment [31].

The EAT-Lancet Commission set as a major target to drastically reduce global GHG emissions by the year 2050. In this initiative, Willett et al. proposed an environment-friendly and healthy dietary pattern, mainly characterized by plant-based food products of high nutritional value, aiming to set a boundary of 5 Gigatons (Gt) of carbon dioxide equivalents (CO2eq) per year related to food production, so as to reduce to about 50% total GHG emissions until 2050. This universal healthy reference diet consisted of fruits and vegetables, whole grains, legumes, nuts and unsaturated oils, and included low to moderate amounts of fish and poultry, and nearly zero consumption of red meat, processed meat, refined carbohydrates and starchy vegetables [25]. Using a measure to quantify adherence to the EAT-Lancet reference diet, namely Planetary Health Diet Index (PHDI) in 3 large United States-based prospective cohorts of males and females with up to 34 years of follow-up, it was shown that a higher PHDI is associated with lower environment impact and reduced risk of total and cause-specific mortality [44].

The term "dietary pattern" is used to denote the combination of foods and beverages (quantity, proportion, variety) and the daily or weekly frequency of consuming each of them [16]. Several dietary patterns have been proposed to be effective in the prevention and treatment of different diseases. Robust scientific evidence supports the beneficial effects of dietary patterns based mostly on plant-derived foods (fruits and vegetables, vegetable oils, whole grains, legumes, nuts and seeds) with a lower intake of animal products and ultra-processed foods [45,46]. The Dietary Guidelines released by the Scientific Advisory Committee of 2021 recommend that a plant-based dietary pattern promotes health and reduces the environmental impact [47]. Plant-based diets minimize carbon and water footprints, and protect simultaneously both human health and the environmental integrity [48]. It has been shown that moving to diets that exclude animal products can significantly reduce global GHG emissions related to food production in Europe by nearly 50% [5]. Furthermore, plant-based dietary patterns have been associated with reduced freshwater and land use, lower biodiversity loss, protective effects on global food security and improved water quality [45].

The "ideal" diet in terms of environmental impact is based on fruits and vegetables, whole-grain starchy foods, legumes, nuts and seeds, unsaturated fats, fish and poultry, and has a very limited consumption of red meat, processed meat products and refined sugars. Unfortunately, the current Europeans' dietary habits depart far away from what is considered as ideal for the protection of global population health and environmental sustainability [5,25].

6. The Overall Health Benefits of the Mediterranean Diet

The positive effects of MD on human health were originally described in the Seven Countries Study by Dr. Keys and his colleagues in the early 1960s. This landmark study was the first to emphasize the protective effects of MD against coronary heart disease (CHD) in people living in the Mediterranean countries [49]. The MDP is widely recognized as a healthy and balanced dietary approach supported by strong scientific evidence, which is considered to be optimal for the maintenance of good physical and mental health, the promotion of longevity and healthy aging, and the reduction of substantial health risks related to a wide variety of diseases including diabetes, obesity, CVD and certain types of cancer, representing the leading mortality risk factors worldwide [13,18,50–53]. A population-based, prospective study with a large number of participants (22,043 adults in Greece), part of the European Prospective Investigation into Cancer and Nutrition (EPIC), has shown that the increased adherence to MD is strongly associated with a significant reduction in

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all-cause mortality [54]. The most consistent scientific evidence for the health benefits of MD has been generated for cardiovascular risk factors and incidence of CVD, but there is also a considerable body of evidence for potential benefits of MD for a wide range of other chronic diseases and health outcomes, including T2DM, metabolic syndrome (MS), obesity, cancer, cognitive decline and CVD mortality [55].

The basic components of the traditional MD as it was originally applied in the olive-growing regions of the Mediterranean basin around the decade of 1960s, included the daily consumption of fruits and vegetables, the frequent intake of nuts, cereals and legumes, and the use of extra-virgin olive oil as the main form of added fat [18]. The original MD is based primarily on seasonal and locally grown foods. The numerous and well-documented protective effects of MD have been established not only in countries of the Mediterranean area, but also in other countries extending far beyond its geographic region [54–56]. Since the year 2010, UNESCO has acknowledged MD as an intangible cultural heritage of the humanity with positive impact on human health and well-being [57,58].

MD is not a strictly plant-based dietary pattern, but is actually partly omnivorous. The plant-based nature of this diet is supported by the following aspects: a high intake of olive oil as the main fat source, fruits, nuts and seeds, freshly and naturally cooked vegetables, whole-meal cereals, herbs and spices, a moderate consumption of fish and poultry, a moderate consumption of red wine, mainly with meals, a low intake of full-fat dairy products, and a very low intake of red meat, processed meats and sweets [16,59]. The MDP is not a unique dietary pattern, but it varies according to the specific country and local special considerations (country-specific variations). The traditional MDP is closer to the traditional diet of Crete (Greece) in the middle of the 20th century (around the 1960s) [25,60].

7. Metabolic and Endocrine Aspects of Mediterranean Diet

MD has been associated with lower incidence rates of new-onset diabetes, and better glycemic control in patients with already established T2DM compared to control diets. Prospective observational cohort studies have shown that adherence to MD is inversely associated with the risk of developing T2DM [61]. In a large cohort of 25,317 female participants from the Women's Health Study, a higher MD adherence was related to a 30% relative risk reduction for T2DM incidence during a 20-year follow-up period [62]. In a meta-analysis of eight prospective studies, the risk of T2DM was 13% lower among those following a MD, while a subsequent analysis of the ATTICA study including 3,042 Greek participants, reported that the medium-high adherence to MD was associated with 49-69% lower 10-year incidence rate of T2DM diagnosis compared to the low adherence [63]. These data were further corroborated in the landmark PREDIMED trial, in which a MD enriched with extra-virgin olive oil or nuts resulted in a 30% T2DM risk reduction compared with the control group [64]. In the field of randomized controlled clinical trials (RCTs), a meta-analysis of 5 RCTs has shown that MD may provide better glycemic control in patients with T2DM and prediabetes, compared with control diets mainly represented by low-fat diets [65]. Apart from improvements in glucose metabolism (fasting and postprandial glucose and insulin levels, glycated hemoglobin), MD can beneficially affect other cardiovascular risk factors as well, such as the lipid profile and blood pressure, in patients with T2DM [66]. It can also alleviate the burden of diabetes-related microvascular (in addition to macrovascular) complications such as diabetic retinopathy and diabetic chronic kidney disease by preventing/delaying their onset and improving their prognosis [67,68]. Furthermore, MD has been proposed as the gold standard nutritional intervention for patients with T2DM and concomitant metabolic dysfunction-associated steatotic liver disease (MASLD), which is a common comorbidity of T2DM with an increasing prevalence worldwide [69]. MD has shown the potential to improve both biochemical and histological features of diabetes-related steatotic liver disease and exert significant hepatoprotective actions [70].

With regard to MS, a meta-analysis of 12 observational studies with a total of 33,847 individuals and 6,342 cases of MS, has shown 19% lower risk of MS associated with greater adherence to MD [71]. In another meta-analysis of two RCTs, there was a 49% greater likelihood of MS remission in those allocated to MD over a follow-up of 2-5 years, compared with those following control diets [65]. In

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terms of potential for weight loss, there is strongly suggestive evidence derived from observational and intervention studies, that MD does not promote weight gain despite its relatively high fat content, but on the contrary, it may be associated with a moderate weight loss and a selective reduction in abdominal adiposity, especially in the setting of energy restriction and combined with increased physical activity [51,72]. It has been suggested that MD can reduce central adiposity and visceral fat accumulation, independently of weight loss. Cross-sectional studies have shown that adherence to MD is inversely associated with markers of abdominal adiposity [73,74]. Interventional clinical trials have also shown that visceral adipose tissue can be significantly reduced with MD [75,76]. These beneficial effects are possibly related to the high content of polyunsaturated (PUFA) and monounsaturated (MUFA) fatty acids, and the low intake of saturated fatty acids (SFA) being the predominant lipid component of visceral fat mass.

The plant-based components of MD (fruits, vegetables, whole grains and nuts) are rich in polyphenols, namely bioactive compounds with important antioxidant and anti-inflammatory properties, that have been shown to reduce insulin resistance and ameliorate multiple cardiometabolic risk factors [77,78]. According to the "fluid aspect concept" of the MD, the olive oil and the low-to-moderate alcohol intake (especially red wine), being principal fluid components of MD, can further contribute to the benefits of MD via their rich polyphenol content. Olive oil contains at least 30 phenolic compounds, while the major red wine polyphenols include flavonols, flavanols, anthocyanin and stilbenes (resveratrol). Overall, the major mechanisms underlying the well-documented beneficial cardiometabolic effects of MD and its important role in the prevention and management of T2DM, obesity, MS and CVD, comprise the following: reduction of oxidative stress and inflammation, improvement of insulin sensitivity and glucose metabolism, modification of plasma lipoprotein composition and function, improvement of fasting lipid profile, attenuation of postprandial lipemia, improvement of endothelial function and reduction of proatherogenic gene expression, modulation of gut microbiota in the direction of a more balanced and biodiverse gut microbiome profile, antithrombotic and immunomodulatory properties [79,80]. Extra-virgin olive oil, in particular, representing the principal functional component of MD being characterized by a high total polyphenol content and balanced composition of MUFA and PUFA, has been suggested to be involved in the upstream and downstream intracellular networks of insulin receptor signaling, playing thus an important role in regulating insulin actions at cellular level [78]. Although not all phenolic compounds of extra-virgin olive oil are systematically absorbed reaching the desired bioavailable/bioactive concentrations within insulin-sensitive tissues, oleacein, through its relatively high lipophilicity accounting for improved survival to gastric acids and enhanced intestinal absorption into systemic circulation, may be capable of inducing insulin-sensitizing actions, which might be clinically relevant for diabetes prevention in people adhering to MD [81].

Beyond its effects on cardiometabolic outcomes, MD has been further proposed as a highly recommended dietary intervention for the prevention and management of a variety of endocrine diseases, including thyroid disorders, gonadal disorders (i.e. polycystic ovary syndrome; PCOS) and neuroendocrine tumors, highlighting the need for interdisciplinary collaboration between endocrinologists and nutritionists for optimizing the outcomes of these patients [82]. A growing body of evidence suggests that MD has the potential to reduce the risk of nodular thyroid disease, autoimmune thyroiditis and thyroid cancer, improve male and female reproductive health, and optimize the therapeutic management of patients with neuroendocrine tumors [82]. Most of these effects can be largely explained by the anti-inflammatory and antioxidant properties of MD related to its high content in phytochemicals [82].

8. Mediterranean Diet and Sustainability

Different dietary patterns may have distinct environmental impacts [83,84]. According to an interdisciplinary committee addressing climate degradation and proposals for a healthy diet and a sustainable food production process, among all the dietary patterns studied, the best pattern was that of MD, and more specifically a diet similar to the Cretan diet, as it was practiced in the mid of the

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20th century [85,86]. This dietary pattern is characterized by a low intake of red meat and a high consumption of plant foods and olive oil [87].

MD may serve as an outstanding model and an exemplary case of a sustainable nutritional system. Apart from its significant beneficial effects on human health, economy and sociocultural aspects [8,88], the MDP is considered to be a sustainable diet which can play an essential role for the environment and CC. The MDP has similar characteristics as other sustainable diets such as vegan diets and the DASH diet (Dietary Approach to Stop Hypertension), characterized by a low consumption of animal products and a positive contribution to biodiversity and local cultural heritage [89].

Table 1 summarizes the major studies investigating the environmental impact of the MDP.

Table 1. A summary of the major studies investigating the environmental impact of the Mediterranean dietary pattern.

Author (year)	Aim of the study	Study design and methods	Study population	Major findings
Filippin D et al. (2023) [2]	To compare two plant-based, isocaloric diets (Vegan diet vs. MD) in terms of their environmental impact	Life cycle assessments were used to investigate total environmental impact of two diets according to relevant Italian dietary recommendations, calculations based on a theoretical 2000 kcal/d diet for one week	NA	The Vegan diet showed ↓ 44% total environmental impact vs. MD, despite the low animal product content of MD. Even a minimal to moderate content of animal products has detrimental impact on the environment, and their reduction can be ecologically beneficial.
Bordoni A et al. (2023) [1]	To evaluate the WF of the recommended Italian diet, which is a version of MD	The WF of various food products were calculated by averaging the data reported in a published dataset in each food category, taking into account Italian eating habits and the available data.	Italian population	The Italian version of MD has ↓ WF. It is necessary to inform consumers, farmers and producers for water-saving choices.
Tucci M et al. (2022) [10]	To compare CF and WF of an Italian-Mediterranean version of the EAT-Lancet reference diet (EAT-IT) with a diet based on Italian Dietary Guidelines	Data related to CF (accounting for GHG) and WF (accounting for water consumption), were retrieved from a multi-level dataset of food	Italian population	Compared to the diet based on Italian Guidelines, the EAT-IT pattern had ↓ CF but similar WF. Protein-rich foods (meat, dairy) were the main contributors to CF and WF in both patterns.

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		commodities, assigning footprint values to food items. Weekly dietary patterns were developed (2500 kcal/d) considering food categories, portions and frequencies of intake		The EAT-IT pattern is sustainable in terms of CF, but individual choices can largely affect environmental outcomes.
Giosuè A et al. (2022) [5]	To propose an ideal dietary pattern for CVD prevention	Systematic review of meta-analyses of prospective studies	European population	The proposed diet had ↓ 48.6% CF compared to the current Europeans' diet.
Castaldi S et al. (2022) [7]	To compare the environmental impact of MD between MD and non-MD countries of EU	A compilation of 3449 CF values of food commodities, based on a standardized methodology, was used to estimate GHG emissions related to food consumption, using 2017 as a reference year.	7 MED countries and 21 non-MED countries of EU	GHG emissions were comparable between MD and non-MD countries, mainly driven by meat over-consumption in the Mediterranean countries.
Rosi A et al. (2020) [90]	To investigate the dietary environmental impact in Italian children, according to their adherence to MD	Observational study Calculations of carbon and ecological footprints	N=172 primary school children living in Parma (8-10 years old)	Carbon and ecological footprints were higher in winter than in summer, and the main dietary contributors were red and processed meat. There was a weak positive correlation between MD adherence and environmental footprints due to higher energy intake. The overall food intake is more important than consumption of specific food groups in terms of environmental implications.
Fresán U et al. (2018) [91]	To evaluate the impact of MD adherence on resource use (land, water,	Life cycle assessments were used to assess the environmental footprint	N=20,363 Spanish University	The higher MD adherence was associated with ↓ land use, ↓ water and energy

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	energy) and GHG emissions in a Mediterranean Spanish cohort	of food item production and processing.	graduates, SUN Cohort (1999-2015)	consumption and ↓ GHG emissions.
Sáez-Almendros S et al. (2013) [92]	To compare current SDP with MDP and WDP in terms of environmental footprints	Food balance sheets and household consumption surveys were used for dietary composition Life cycle assessments were used to assess environmental footprints	Spanish population	The increasing adherence to MDP was associated with ↓ GHG emissions (72%), ↓ land use (58%), ↓ energy consumption (52%) and ↓ water consumption (33%). The adherence to WDP increased all these indices (12-72%)
Álvarez-Álvarez L et al. (2024) [84]	To evaluate the impact of a 12-month MD intervention on environmental sustainability	Longitudinal analysis of the PREDIMED-Plus trial cohort, which was a multicenter, randomized, controlled 8-year intervention trial on MD	N=5,800 participants of the PREDIMEDPlus study	The high adherence to MD for one year was associated with lower GHG emissions, land use, energy use, acidification and eutrophication.

CF: carbon footprints; CVD: cardiovascular disease; EU: European Union; GHG: greenhouse gas; MD: Mediterranean diet; MDP: Mediterranean dietary pattern; NA: non-applicable; SDP: Spanish dietary pattern; WDP: Western dietary pattern; WF: water footprints.

In Spain, the MDP is considered as a traditional dietary model but also a healthy and environment-friendly dietary pattern. A large number of Spanish studies suggest that the MDP may contribute to high sustainability of food production and consumption systems, in parallel with a positive impact on public health [92]. According to the study by Sáez-Almendros et al., the adherence of the Spanish population to the MDP is able to decrease the environmental footprints. The increased adherence to the MDP in Spain could lead to the reduction of GHG emissions by 72%, land use by 58%, energy consumption by 52% and water consumption by 33%, as opposed to a western dietary pattern which would increase all these environmental factors by 12%-72% [92].

According to another observational study conducted in Spain (the SUN cohort study), greater adherence to the MDP was associated with lower land use, lower energy and resource consumption and reduced GHG emissions [91]. Another relevant longitudinal study has been conducted in Spain, with data collected at baseline and after one year of MD intervention in participants of the PREDIMED-Plus trial cohort, which was a multicenter, randomized, controlled 8-year intervention trial on the effects of MD [52,65]. According to this study, the high adherence to the MDP was strongly associated with lower environmental impact in five specific environmental domains: GHG emissions, land use, energy use, acidification and eutrophication. The results of the latter study have shown that after one year of dietary intervention with the MDP, these five indicators were all decreased. Considering that meat products have the highest environmental impact across all these five dimensions, the MDP with a lower consumption of animal foods may reduce even more the negative diet-related environmental impact [93–95].

An additional study conducted by Metin et al. in a total of 1,797 participants aimed to evaluate the relationship between adherence to the MDP, healthy and sustainable eating behaviors and CC awareness in adults [96]. The study reported a statistically significant positive correlation between

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three specific scores: the MDP Adherence Scale (MEDAS), the Sustainable and Healthy Eating Behaviors Scale, and the Climate Change Awareness Scale. The study found a significant relationship between CC awareness, sustainable and healthy eating behaviors and adherence to the MDP [96].

Figure 1 illustrates in a graphical way the sustainability features of MD, which make it an "ideal" dietary model for the protection of planetary health.

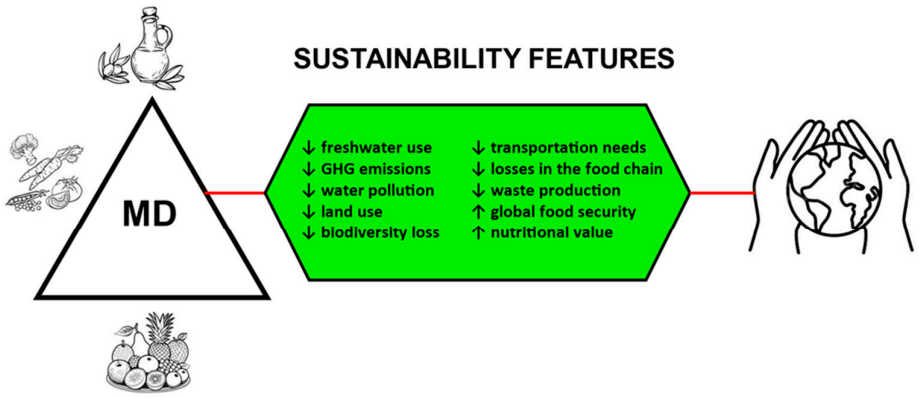

Figure 1. A graphical presentation of the multiple sustainability features of Mediterranean diet contributing to its positive ecological fingerprint. GHG: greenhouse gas; MD: Mediterranean diet.

9. Identifying Barriers to Mediterranean Diet Widespread Implementation

The adherence to healthy and sustainable dietary patterns such as the MD, is not easy at all. The adoption and successful implementation of this diet should be considered as a real challenge for people in the developed world, but also in the developing countries, where people suffer mostly from poverty and malnutrition [13,97,98].

The question of whether worldwide MD applicability is feasible still remains, mainly due to barriers related to different cultures and traditions. Studies have shown that the adherence to MD might be difficult for populations living far from the Mediterranean basin [99]. The main factors that have been recognized to influence the adherence to the MDP are financial, sociocultural, cognitive, sensory, motivational, demographic, and also related to accessibility and availability of MD food products [100,101]. A review by Gibbs and Cappuccio, in 2022, outlined the most prominent perceived and objective barriers preventing people from transitioning to plant-based diets. According to this review, the main barriers to widespread adoption of plant-based dietary patterns, including MD, comprised meat appreciation, health concerns related to potential nutrient deficiencies, convenience, taste factors and cost issues [45]. Another relevant study explored the public understanding of the link between food, environment and CC, and more specifically, the attitudes towards reducing meat consumption. The study revealed that participants were not aware of the association between meat consumption and CC, but also of the magnitude of personal meat consumption's effect in the global context of CC. Participants were also unwilling to reduce their personal meat consumption [102].

10. Concluding Remarks and Critical Perspectives

Our eating habits and individual food choices can influence the connection between food production systems and critical environmental dimensions such as GHG emissions and global earth warming. Animal-based products contribute significantly to the increased environmental footprints of diets. Dietary patterns such as the western dietary pattern, with a high consumption of animal

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food products, can lead to environmental degradation and relatively high GHG emissions. In opposite, it has been shown that a dietary shift to the MDP can significantly reduce the major environmental impacts such as GHG emissions, land use, energy and water consumption.

The adoption of healthy dietary patterns is crucial to achieve sustainable development as a means to counteract food insecurity and malnutrition. There is an urgent need for public health strategies to achieve healthy sustainable diets, improving energy balance and dietary options towards predominantly plant-based diets aligned with healthy eating guidelines. In parallel with the adoption of sustainable diets such as the MDP, scientists all over the world should take different factors into consideration, including local climate and culture settings, water availability, the diversity of agricultural production systems and the physical properties of soil and land. It is suggested that future studies should adopt a more holistic approach and propose the concept of a "Planeterranean" diet, which could be applicable worldwide [103,104].

Overall, the available scientific evidence clearly suggests that a diet high in plant-based whole foods makes up the dietary pattern which is most associated with reduced morbidity and mortality, increased longevity and improved quality of life. Reducing meat consumption is also fundamental from an environmental perspective, in order to optimize diet sustainability. The MDP, as a typical example of a plant-based dietary pattern, is widely recognized as a sustainable dietary model which promotes optimal individual and planetary health. The MDP gained enormous attention mainly due to its proven effects on different aspects of health, but also due to its taste that facilitated a widespread popularity even among non-Mediterranean populations. It is important, however, to emphasize that the MDP is not just a list of ingredients, foods and recommendations. It has many underestimated aspects of dietary behavior such as the consumption of spices and herbs, cooking methods, food quality, lifestyle and sleeping patterns as well as connection with the territory, which should be also implemented in order to take full advantage of its beneficial environmental impact [104].

Despite strong scientific evidence substantiating the beneficial effects of the MDP on the environment, there are still several barriers to its widespread implementation, especially in countries located beyond the Mediterranean basin, which have not been adequately addressed yet. Country-specific variations, adapted to the local culture and culinary tradition of each country, need to be designed and validated in terms of their environmental impact. Furthermore, although a number of studies have used specific indicators of environmental sustainability and provide compelling evidence that they are all improved with MD, there is no study assessing a complete set of environmental dimensions in the comprehensive and systematic way that the EAT-Lancet Commission project did with regard to the proposed healthy reference diet. Last but not least, whether reducing further the animal product intake in the setting of a modified MD version similar to the Vegan diet would elicit additional ecological benefits, remains to be investigated with future studies. In this context, nutrient adequacy aspects need to be meticulously considered.

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