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Plant bioactive compounds from Mediterranean diet improve risk factors for metabolic syndrome

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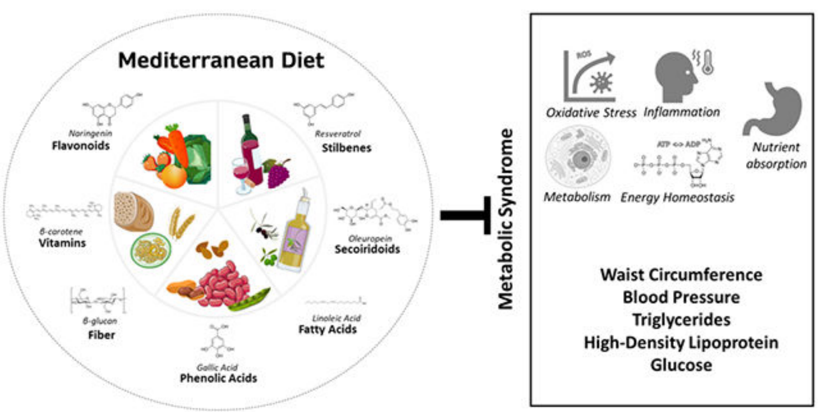
Abstract

Mediterranean (Med) dietary pattern consists of moderate or high consumption of foods that are linked to reduced risk factors for metabolic syndrome (MetS). This comprehensive review evaluates studies on Med diet-representative foods and beverages, such as red wine and olive oil, to understand the inverse associations of Med diet and MetS. The intake of dietary fiber, unsaturated fatty acids, vitamins, and polyphenols — including flavonoids and stilbenes — help to explain the benefits of Med diet on abdominal adiposity, glucose intolerance, hyperlipidemia, and high blood pressure to some extent. Antioxidant and anti-inflammatory properties of polyphenols as well as the effects of unsaturated fatty acids on lipid metabolism are part of the underlying mechanisms. Overall, this review shows that dietary interventions using Med diet components improve MetS health markers in humans and/or rodents.

Graphical Abstract



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Keywords

diabetes; hypertension; obesity; olive; polyphenols; wine

1. Introduction

Metabolic syndrome (MetS) consists of a group of interrelated metabolic conditions resulting in the increased prevalence of obesity and other diseases, which gives rise to a major clinical challenge world-wide. These disorders collectively increase the risk of developing chronic inflammation and diseases, such as type 2 diabetes mellitus by 5-fold and cardiovascular disease by 2-fold (Eckel, Grundy, and Zimmet 2005; Grundy 2008; Kahn, Wang, and Lee 2019; Martin, Mani, and Mani 2015; Rochlani et al. 2017; Tuomilehto 2005). Three of the five following conditions need to be met for the diagnosis of MetS: abdominal obesity (waist circumference), elevated triglycerides levels, reduced high density lipoprotein (HDL) cholesterol, hypertension, and impaired fasting glucose; criteria for MetS diagnosis varies according with MetS definitions (Alberti et al. 2009; Eckel, Grundy, and Zimmet 2005). Two of the essential components that serve as the main driving force behind MetS are fat accumulation and insulin resistance (Andersen, Murphy, and Fernandez 2016; Grundy 2008; Alberti et al. 2009). Visceral fat accumulation is associated with dysfunction of adipose tissue causing metabolic stress in organs of the digestive and endocrine system, such as liver and pancreas (Andersen, Murphy, and Fernandez 2016; Boulangé et al. 2016). In adults, adipose tissue expansion occurs through adipocyte hypertrophy, meaning the adipocytes become engorged (Andersen, Murphy, and Fernandez 2016; Kahn, Wang, and Lee 2019). These adipocytes tend to cause endoplasmic reticulum and mitochondrial stress responses along with extracellular environmental stress leading to the chronic, pro-inflammatory state within the adipose tissue (Andersen, Murphy, and Fernandez 2016). The pro-inflammatory cytokines produced by the recruited inflammatory leukocytes, hypertrophic adipocytes, and macrophages promote the aforementioned metabolic dysfunctions (Andersen, Murphy, and Fernandez 2016; Boulangé et al. 2016). Susceptibility factors that are usually required for MetS to occur include genetic factors, aging, endocrine disorders, low-density lipoprotein (LDL) and HDL plasma concentrations, and certain lifestyle factors, such as diet and exercise (Grundy 2008; Stone and Saxon 2005).

Early diagnosis and promising interventions for treatment are imperative for controlling these metabolic conditions (Grundy 2008; Rochlani et al. 2017; Stone and Saxon 2005). Although there are approved drugs intended to treat individual MetS-associated conditions, such antidiabetic, antihypertensive, antihyperlipidemic, and anti-obesity drugs, these drugs may have contradictory effects (Russo, Autelitano, and Bisanti 2008). For example, some antidiabetic drugs can lead to weight gain, while some antihypertensive and antihyperlipidemic drugs can lead to insulin resistance (Phung et al. 2010; Berne, Pollare, and Lithell 1991). This suggests a need for novel approaches to treating MetS. While it is unlikely that a single intervention will completely restore patients with MetS to a healthy state, the utilization of multiple complementary treatments may improve the health and wellbeing of patients, and for this reason additional beneficial treatments for MetS are needed. Although Western diets, rich in sugar and fat, are associated with high risk of MetS, adherence to a 'healthy' and polyphenol-rich diet can help to manage and reverse the effects of MetS (Grundy 2008; Stone and Saxon 2005; Castro-Barquero et al. 2020; Babio et al. 2014).

One of the main contributing environmental factors for MetS development is dietary patterns (Stone and Saxon 2005; Hosseini, Whiting, and Vatanparast 2016). The relationship of dietary patterns and MetS was previously reviewed by using population-based studies (Hosseini, Whiting, and Vatanparast 2016). The Western diet, consisting of red meat, refined cereals, sweetened beverages, and processed food, is considered an 'unhealthy' diet due to its effects on MetS risks, including lipid profile and anthropometric measurements (Drake et al. 2018; Hosseini, Whiting, and Vatanparast 2016). Although finding the culprit within a diet for MetS development is controversial, these effects of an 'unhealthy' diet may be due to high calories, refined carbohydrates, saturated fat, and cholesterol content altering the circulating levels of triglycerides, LDL, and HDL (Grundy 2008; Stone and Saxon 2005). Moreover, high alcohol consumption increases the risk of MetS in comparison to moderate alcohol consumption (Clerc et al. 2010). On the other hand, Mediterranean (Med) and the Dietary Approaches to Stop Hypertension (DASH) diets are the two diets frequently suggested by health experts and researchers that are associated with the reduced risk of MetS (Asghari et al. 2016; Finicelli et al. 2019; Hosseini, Whiting, and Vatanparast 2016; Babio et al. 2014). The commonality between the two diets, DASH and Med, is a high intake of fruits and vegetables and whole grains while maintaining a low intake of meals high in saturated fat (Finicelli et al. 2019; Steinberg, Bennett, and Svetkey 2017; Campbell 2017). The bioactive compounds linked to the beneficial effects of these two dietary patterns include polyphenols and dietary fiber (Asghari et al. 2016; Steinberg, Bennett, and Svetkey 2017; Finicelli et al. 2019). Due to the overall health benefits associated with these two diets, nutritional interventions recommending a 'healthy' diet are considered for the prevention and management of MetS. Med diet is one of the 'healthy' diets that has been mostly extensive investigated (Handu and Piemonte 2022). Thus, we reviewed studies of Med diet-representative foods, beverages, and bioactive compounds on MetS risks, which may be useful to understand the effects of Med diet against MetS development. The social and behavioral aspects that the effects of Med diet on MetS, such as lifestyle, diet adherence, and exercise, were not the focus of this review.

2. Mediterranean diet

Med diet reflects the dietary patterns followed in the early 1960s by inhabitants of the Mediterranean sea basin, primarily in Greece and Southern Italy (Bach-Faig et al. 2011; Davis et al. 2015; Trichopoulou et al. 2014; Trichopoulou et al. 2003). The Med diet is composed of a high intake of olive oil, vegetables, fruits, whole-grain cereals, legumes, nuts, and a moderate consumption of red wine, fish, and low-fat dairy along with low consumption of red meat, butter, sweets, and pastries (Finicelli et al. 2019; Davis et al. 2015; Estruch et al. 2018). Med diet composition consists of mostly carbohydrates (43% total kcal) and total fat (37% total kcal), with a moderate intake of proteins (15% total kcal). The consumption of unsaturated fatty acids is twice higher than saturated fatty acids, and Med diet also provides about 33 g of dietary fiber daily. In addition to the macronutrients, Med diet is a good source of vitamins and minerals that could help to meet the Recommended Dietary Allowances (RDAs) and Adequate Intakes (AI). For example, Med diet provides 225 mg/day of vitamin C (RDA = 15-120 mg/day), 508.2 μg/day of folate (RDA = 150-600 μg/day), and 3614.3 mg/day of potassium (AI = 400-3400 mg/day) (Davis et al. 2015). Med diet composition is not particularly different than the average American diet if we account the macronutrients; average carbohydrates, fat, and protein intakes by both sexes in years 2013-2016 were 47%, 35%, and 16% of total kcal, respectively (National Center for Health Statistics 2021). That suggests that other food components, such as dietary fiber, are at least partially responsible for its beneficial effects on human health. Indeed, the daily intake of fiber (16 g) by the average American is much lower than the amount of dietary fiber in Med diet (Grooms et al. 2013; Davis et al. 2015). Moreover, Med diet is a good source of bioactive compounds from plant secondary metabolism, such as polyphenols (Tresserra-Rimbau et al. 2013; Davis et al. 2015). The intake of total polyphenols (820 mg/day), and its subclasses: flavonoids (443 mg/day) and phenolic acids (304 mg/day) from a Med diet, followed by a Spanish population at high cardiovascular risk (PREDIMED), may also help to explain its effects on MetS (Tresserra-Rimbau et al. 2013). Although Mediterranean Diet Foundation had summarized Med diet in a dietary pyramid (Fundación Dieta Mediterránea 2010), it is important to highlight that the food components of Med diet across studies here revised may vary according to scientific goals and studied populations. Furthermore, we present here findings obtained from meta-analyses of clinical trials that employ interventions using polyphenol-based extracts/foods. It is worth noting that the intake of these food components may not accurately reflect their habitual intake on populations. However, studies on the biological effects of polyphenols suggest the beneficial effects of polyphenol-rich foods on the risk of MetS development, whether they focus on the habitual intake of polyphenols or are interventional (e.g. PREDIMED). There are inconsistencies that could be explained by differences in methodology or population, but the habitual/interventional dietary intake of polyphenols was inversely associated with MetS and cardiometabolic risk factors in Polish, Iranian and Spanish people (Zujko et al. 2018; Aali et al. 2022; Tresserra-Rimbau et al. 2013).

Med diet is inversely associated with the incidence of MetS and associated diseases, such as obesity, diabetes, and cardiovascular disease (Finicelli et al. 2019; Guasch-Ferré and Willett 2021). Randomized clinical trials showed that Med diet improved anthropometric parameters, especially the waist circumference (i.e. central obesity) of MetS patients (Montemayor et al. 2022; Babio et al. 2014). Blood pressure, HDL, and fasting plasma glucose (FPG) levels were also improved in those MetS patients after 6 and/or 12 months, which were associated with the increased fruits, vegetables, nuts, and fish consumption (Montemayor et al. 2022). The bioactive compounds present in Med diet may also be responsible for its effects on metabolism. Consistently, a cross-sectional study using data from an energy-reduced Med diet trial (PREDIMED-Plus) linked the metabolic effects of Med diet to polyphenols (Castro-Barquero et al. 2020). Other epidemiological and clinical studies of Med diet on MetS risks, including PREDIMED, were previously summarized by Finicelli et al. (2019). Altogether, these studies showed that Med diet reduces the risk of MetS development, ameliorating the metabolic conditions. These effects of Med diet on

MetS can be attributed to certain Med diet-related food components: red wine, olive oil, legumes, nuts, whole-grain cereals, fruits, and vegetables.

2.1 Red wine and grapes

Moderate consumption of red wine with meals is one of the characteristics of Med diet, and beneficial effects of red wine are primarily through the non-alcoholic portions containing high polyphenol content, but also ethanol content affects human health (Santos-Buelga, González-Manzano, and González-Paramás 2021). It has long been suggested that red wine may help prevent the incidence of cardiovascular disease and wine-drinking has been linked to the so-called ‘French Paradox’ (Renaud and Gueguen 1998). The French Paradox is a concept that reflects the disparity in cardiovascular disease between the population of France and the populations of other developed countries despite the high intake of animal fat by the French population (Criqui and Ringel 1994). Early studies suggested that this reduction in the incidence of cardiovascular disease is a result of increased alcohol consumption in the form of wine, with studies suggesting that daily consumption of any form of alcohol may reduce the risk of heart disease (Criqui and Ringel 1994; Fragopoulou and Antonopoulou 2020). However, a meta-analysis found that a reduction in vascular disease was observed in adults who consumed 21 g/day of alcohol in the form of wine, including red wine, and a smaller reduction was observed in adults who consumed a similar amount of alcohol in the form of beer daily, while no improvement in vascular health was observed in adults who consumed a similar amount of alcohol in the form of spirits (Costanzo et al. 2011). Consistently, moderate consumption of wine (1-2 drinks/day) was correlated with favorable cardiovascular health in a multi-ethnic cohort study, while beer and liquor were correlated with poorer cardiovascular health (Ogunmoroti et al. 2021). Moderate consumption of red wine exerted beneficial effects on lipid and glucose metabolism by modifying lipoproteins and insulin resistance, which was measured by homeostasis model assessment of insulin resistance (HOMA-IR) in men at high cardiovascular disease risk (Chiva-Blanch et al. 2013). Dealcoholized red wine and red wine, containing 733-798 mg of total polyphenols, improved insulin sensitivity when compared to gin (Chiva-Blanch et al. 2013). The beneficial effects of red wine were associated with its polyphenols, including resveratrol in the same study (Chiva-Blanch et al. 2013). In addition to stilbenes (e.g. resveratrol), the most common polyphenols found in red wine include flavonoids (e.g. catechins, quercetin, and malvidin) and phenolic acids (e.g. caffeic and gallic acids) (Barbalho et al. 2020; Markoski et al. 2016; Gutiérrez-Escobar, Aliaño-González, and Cantos-Villar 2021). The molecular structures of resveratrol, quercetin and caffeic acid are shown in Figure 1. A recent meta-analysis found that of the studies included in the analysis investigating the effect of red wine polyphenols on blood pressure, 100% of animal studies found an improvement in vascular function and 84% found an improvement in blood pressure (Weaver et al. 2021). This was compared to human studies which found a significant lowering of systolic blood pressure, but less consistent and pronounced improvements compared to the animal studies (Weaver et al. 2021). This suggests that the decrease in adverse vascular events and MetS risk is a result of molecular components of red wine other than alcohol, such as polyphenols. High intake of alcohol, even in the form of wine, can cause detrimental effects to specific populations. For instance, high intake of red wine (2-3 drinks/day) elevated blood pressure in premenopausal women, while dealcoholized red wine and low intake of red wine (0.5-1 drink/day) did not change blood pressure (Mori et al. 2015). Therefore, we still need to consider the potential detrimental effects of alcohol before we recommend including red wine in a diet. Med diet guidelines suggest moderate red wine consumption (1-2 drinks/day), limiting alcohol consumption to below 20 g/day for women and 40 g/day for men (Santos-Buelga, González-Manzano, and González-Paramás 2021).

Some clinical studies have shown the effects of grape polyphenols by using different grape extracts, including from pomaces, solid residues from winemaking, rather than wine (Asbaghi, Nazarian, et al. 2020; Lupoli et al. 2020; Mohammad, Shahnaz, and Sorayya 2021; Barona et al. 2012; Millar et al. 2018; Martínez-Maqueda et al. 2018). Recent meta-analyses found that treatment of clinical study participants with grape seed extract, or grape polyphenols resulted in a significant decrease in FPG, total cholesterol, LDL, triglycerides, and/or C-reactive protein (CRP), but no change in body weight, or HDL levels (Asbaghi, Nazarian, et al. 2020; Lupoli et al. 2020). Moreover, a recent clinical trial showed that the daily supplementation with 100 mg of grape polyphenols extract reduces insulin levels and HOMA-IR in adolescents with MetS (Mohammad, Shahnaz, and Sorayya 2021). Although these studies suggest the beneficial effects of grape polyphenols, other reports have shown that beneficial effects of grapes polyphenols on MetS risk factors are inconsistent. The flavonoids in grapes are the most common polyphenols, but their content is largely dependent on the variety and growth conditions (Barbalho et al. 2020; Gutiérrez-Escobar, Aliaño-González, and Cantos-Villar 2021). These variations of polyphenols content may partially explain the inconsistencies, as most studies do not identify and quantify all polyphenols in their interventions.

The effects of grape polyphenols on all MetS conditions are variable according to the study context and length of the intervention. For example, a clinical study reported that grape polyphenol extract lowered blood pressure for men with MetS, but did not alter any other MetS variables after 30 days (Barona et al. 2012). Another study reported that the supplementation with freeze dried grape powder or grape pomace to adults with at least two MetS factors significantly lowered fasting plasma triglycerides or fasting insulin levels, but did not affect HDL levels or any other MetS marker after 4-6 weeks (Millar et al. 2018; Martínez-Maqueda et al. 2018). Although there is some evidence that grape polyphenols can improve insulin sensitivity, there is no consistent evidence that grape polyphenols affect glycemia, blood pressure, or lipid levels (Woerdeman et al. 2017; Pérez-Ramírez et al. 2020). For instance, a dietary supplement containing grape pomace extract did not have a significant effect on glucose metabolism and oxidative stress after one single dose on adults with abdominal obesity (Pérez-Ramírez et al. 2020). Grape polyphenols in different food matrices in form of tablets, beverage, or food have different bioavailability, which is another factor that may affect their biological effects (Rotches-Ribalta et al. 2012). Interestingly, a 3-month study with adult men with metabolic conditions for MetS found that when participants consumed wine grape pomace flour within beef burgers daily there was significant improvement in FPG and plasma antioxidant levels, and a significant reduction in oxidative stress markers compared to daily consumption of burgers without grape pomace supplementation for one month (Urquiaga et al. 2018). Taken together, these clinical studies suggest that health outcomes of grape polyphenols depend largely on different variables, such as dose and length of interventions.

It remains unclear whether and in what context the intake of grape polyphenols results in improvement of MetS in humans, even though evidence from continued research on grapes suggests an improvement in multiple endpoints in animal models of MetS. In another study, a reduction in atherosclerosis and increased survival was detected in a mouse model of ischemic heart disease in mice fed a diet supplemented with red wine grape pomace, with the increase in survival absent in mice fed a fiber-supplemented diet control, suggesting that grape polyphenols are responsible for the protection from ischemic heart failure (Rivera et al. 2019). Previous studies have suggested that grape polyphenols have an anti-hyperglycemic effect in animal and cell line models (Pinent et al. 2004; Meeprom et al. 2011; Rodriguez Lanzi et al. 2016). Moreover, studies have reported that grape seed flour and grape polyphenols can decrease weight gain and change lipid metabolism in animal models of obesity (H. Kim et al. 2015; Serrano et al. 2017; Auberval et al. 2017; Zagayko et al. 2013). The translation to humans of these studies is still limited, but they show the beneficial effects of grape polyphenols on MetS conditions with insights on the mechanisms of action.

Resveratrol, a stilbene group of polyphenols present in grapes and red wine up to around 100 mg/L, is usually associated with counteracting the underlying mechanisms of MetS due to its anti-inflammatory and antioxidant properties (Auberval et al. 2017; Gutiérrez-Escobar, Aliaño-González, and Cantos-Villar 2021). Although there is extensive research primarily on resveratrol, the anti-inflammatory and antioxidant properties are somewhat generalizable to other polyphenols present in grapes and wine (Gutiérrez-Escobar, Aliaño-González, and Cantos-Villar 2021; Nallathambi et al. 2020). Inflammation is a common feature associated with obesity and MetS that results in the production of reactive oxygen species (ROS) (Asbaghi, Nazarian, et al. 2020; Andersen, Murphy, and Fernandez 2016; Boulangé et al. 2016; Lee et al. 2022). Polyphenols act directly as antioxidants by scavenging ROS and indirectly by inducing the upregulation of the antioxidant phase II xenobiotic metabolizing enzymes (e.g., heme oxygenase and superoxide dismutase) (Seyyedebrahimi et al. 2018; J. Kim et al. 2019). Polyphenols' antioxidant and anti-inflammatory properties were mechanistically linked with improvement of insulin resistance and other metabolic dysfunctions (Ngamsamer, Sirivarasai, and Sutjarit 2022; Su et al. 2022; Nallathambi et al. 2020). In humans, polyphenol-rich foods have been suggested to protect against MetS-induced oxidative stress by decreasing fasting glucose levels (Zujko et al. 2018). Indeed, resveratrol reduced the inflammation-induced oxidative stress in kidney cells (Lee et al. 2022). Consistently, resveratrol inhibited the nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB), a transcription factor responsible for gene expression of pro-inflammatory cytokines (Nallasamy et al. 2021). Grapes and wine, together with resveratrol and other grape polyphenols (e.g. anthocyanins and proanthocyanidins), have long been an area of interest to improve MetS conditions (Ngamsamer, Sirivarasai, and Sutjarit 2022; Nallathambi et al. 2020). Although the effective doses of grape/wine polyphenols are still not definitive, grape products overall improved total antioxidant capacity in humans (Sarkhosh-Khorasani, Sangsefidi, and Hosseinzadeh 2021). All in all, wine and grape polyphenols are part of the beneficial effects of Med diet on MetS, and some of the evidence is summarized in Figure 1.

2.2 Olive oil

Olive oil, one of the food components typical in the Med diet, contains high levels of valuable bioactive components such as essential fatty acids (Rabail et al. 2021). The composition of olive oil is about 70% monounsaturated fatty acids (MUFA; e.g. oleic acid), 12% polyunsaturated fatty acids (PUFA; e.g. linoleic acid; Figure 2) and 15% saturated fatty acids (SFA; e.g. palmitic and stearic acids) (Rabail et al. 2021). Olive oil contributes to the average intake of MUFA (19% total kcal), PUFA (5% total kcal), and SFA (9% total kcal) from Med diet (Davis et al. 2015). In addition to fatty acids, polyphenols are found in olive oil, which contributes to the biological effects of olive oil (Jimenez-Lopez et al. 2020).

Extra virgin olive oil contains more polyphenols than non-virgin olive oil, and its high consumption (>50 g/day; equivalent to ≥ 4 tablespoons) was associated with reduction of cardiovascular disease and mortality in the PREDIMED study (Jimenez-Lopez et al. 2020; Guasch-Ferré et al. 2014; Estruch et al. 2018). The secoiridoids (e.g. oleuropein; Figure 2), phenolic alcohols (e.g. hydroxytyrosol; Figure 2), phenolic acids (e.g. hydroxybenzoic, coumaric and ferulic acids) and flavonoids (e.g. luteolin and apigenin) are the most abundant polyphenol groups in extra virgin olive oil (Jimenez-Lopez et al. 2020). Another cross-sectional PREDIMED study showed that virgin olive oil, rather than refined olive oil or pomace olive oil, is inversely associated with peripheral artery disease (Sánchez-Quesada et al. 2020). Indeed, the consumption of high-polyphenolic extra virgin olive oil decreased cardiovascular disease risk by increasing flow-mediated vasodilatation in type 2 diabetes patients, in comparison to non-virgin olive oil (Njike et al. 2021). A recent review of clinical trials showed that virgin olive oil improves triglycerides, HDL levels, and inflammatory markers especially in patients with MetS (Tsartsou et al. 2019). In the PREDIMED study, Med diet with virgin olive oil increased HDL levels and apolipoprotein A, the backbone of HDL particles (Solá et al. 2011). Olive oil may improve cholesterol efflux capacity by improving HDL size, composition, stability, and oxidative status in humans (Hernáez et al. 2014; Fernández-Castillejo et al. 2017). Therefore, the high intake of extra virgin olive oil is recommended to those following Med diet. However, the effects of olive oil on MetS conditions are still debated (Figure 2). A meta-analysis review showed the antioxidant potential of olive oil, and its components (i.e. oleic acid, and the phenolic hydroxytyrosol), but olive oil and its components do not contribute to improve lipid profile, body composition, glycemic profile, and blood pressure (Pastor, Bouzas, and Tur 2021). The health status of the population may contribute to the controversial effects of olive oil on metabolism; the intake of 50 mL high-polyphenols extra virgin olive oil reduced glucose levels, and insulin resistance after 4 h in healthy individuals, but not in MetS patients. (D’Amore et al. 2016). Moreover, olive oil did not change cholesterol efflux capacity, despite the increased HDL levels, independently on polyphenol content in healthy subjects (Sarapis et al. 2022). These epidemiological and clinical studies suggest that extra virgin olive oil contributes to the effects of Med diet on MetS conditions, even though the improvements of MetS conditions may be mostly associated with Med diet as a whole, rather than only olive oil (Tsartsou et al. 2019).

Pre-clinical studies have shown that extra virgin olive oil ameliorates MetS risk factors in rodent models (Zhao et al. 2019; Prieto et al. 2018). 10-20% extra virgin olive oil (w/w) resulted in improved body weight, lipid profile, and insulin resistance of high fat diet (HFD)-fed rodents, in comparison to rodents consuming a HFD richer in saturated fat from lard or butter (Zhao et al. 2019; Prieto et al. 2018). Others have shown that virgin olive oil improves cardiovascular parameters, including systolic blood pressure in hypertensive rats (Villarejo et al. 2015; Alcaide-Hidalgo et al. 2020; Domínguez-Vías et al. 2021). Extra virgin olive oil at 5.5% in a HFD were not able to reduce body weight, but extra virgin olive oil improved the circulating triglycerides levels and inflammation-related molecular targets in aortic vessel tissues of rats (Flori et al. 2020). Extra virgin olive oil improved MetS risks, even at lower concentrations, by changing underlying metabolic changes characteristic of MetS in rodents.

The beneficial effects of olive oil on MetS risks were previously linked to its fatty acids, polyphenols, and peptides. MUFA-rich olive oil (21% total kcal) reduced body weight, triglycerides, and insulin values with the reduction of atherosclerotic plaque formation in mice with MetS, in comparison to mice fed with SFA-rich cow's milk cream (Naranjo et al. 2017; Montserrat-de la Paz et al. 2019). MUFA-rich olive oil causes the upregulation of the cytokine osteoprotegerin (OPG) and downregulation of receptor activator of nuclear factor kappa-B ligand (RANKL), molecular targets involved in aortic calcification (Naranjo et al. 2017). However, other bioactive components of olive oil contribute to its effects on the cardiovascular system. For example, olive oil's peptides act as antihypertensives by inhibiting the angiotensin-converting enzyme (ACE), which regulates the volume of fluids in the body (Alcaide-Hidalgo et al. 2020). Moreover, the anti-inflammatory and antioxidant properties of extra virgin olive oil containing polyphenols was associated with aortic vessel sprouting (Flori et al. 2020). Olive oil and its polyphenols downregulate the pro-inflammatory cytokines in adipocytes, and monocytes (Bordoni et al. 2019; García-Escobar et al. 2017; Carpi et al. 2019). In vivo, MUFA-rich olive oil reduced inflammation by reducing circulating levels of tumor necrosis factor-alpha (TNF-α) and interleukin 6 (IL-6) in the adipose tissue of MetS mice after 8 weeks (Montserrat-de la Paz et al. 2019). Others have reported the stimulatory effects of olive oil on the cannabinoid system via CB2 receptor, inhibiting adipogenesis and inflammation in adipose tissue of mice (Notarnicola et al. 2016). Also, changes on gut microbiota due to olive oil have been correlated with the improvement of MetS conditions (Zhao et al. 2019; Prieto et al. 2018). All in all, the effects of polyphenols, MUFA, and peptides from olive oil on metabolism help to explain the effects of Med diet on MetS conditions. Moreover, these suggest that the replacement of SFA-rich animal fats to MUFA-rich extra virgin olive oil is a dietary intervention that improve overall health.

2.3 Nuts and legumes

Med diet is composed of a high intake of nuts (e.g. walnuts and almonds) and legumes (e.g. chickpeas, beans, and lentils) (Finicelli et al. 2019; Davis et al. 2015). Nuts and legumes are good sources of proteins, fat, dietary fiber, and polyphenols. For instance, cooked chickpeas (100 g) contain 8.9 g of protein, 2.6 g of fat, 7.6 g of dietary fiber, and more than 100 mg of polyphenols (Gupta et al. 2017; Huang et al. 2020; U.S. Department of Agriculture 2019). As another example, dry roasted walnuts (100 g) contain 14.3 of protein, 60.7 of fat, 7.1 of dietary fiber, and more than 2 g of polyphenols (Vinson and Cai 2012; U.S. Department of

Agriculture 2019). Nuts and legumes recommended intakes vary from 1-4 serving portions weekly up to 1 portion at every meal, but it is important to note that the serving size for nuts (≈ 28 g) is smaller than for legumes (≈ 150 g) (Davis et al. 2015; Guasch-Ferré and Willett 2021; Ministry of Health and Welfare 1999; Bach-Faig et al. 2011). The increased intakes of nuts and legumes in Med diet were associated with the improvements of MetS conditions, and their composition contributes to their metabolic effects (Huang et al. 2020; Montemayor et al. 2022; Julibert et al. 2020).

The effects of nuts on MetS conditions in humans are still debatable; while some studies suggest nuts consumption reduces the risk of developing MetS and its associated diseases, others suggest that the Med diet as a whole is more strongly associated with MetS (Cubas-Basterrechea et al. 2022; Julibert et al. 2020; Galié et al. 2021; Ghosn et al. 2021; Ahola et al. 2021; Hosseinpour-Niazi et al. 2021). For example, nuts consumption was associated with improvement of MetS conditions, except glucose levels, in patients following energy-restricted Med diet over a period of one year (Julibert et al. 2020). Participants who consumed more nuts, on average an increase of 37 g nuts/day, had greater improvement on MetS by decreasing body weight, body mass index (BMI), and triglycerides levels. The same study suggests that the increased adherence to Med diet and consumption of extra virgin olive oil, together with nuts consumption, contributed to the significant effects on MetS conditions (Julibert et al. 2020). Another recent study has reported that nuts intake (50 g/day) was not associated with improvement of glucose metabolism, nor other MetS conditions, but Med diet reduced glucose and insulin levels after 2 months (Galié et al. 2021). Although these suggest that nuts intake in Med diet is not the only factor responsible for the effects of the Med diet on MetS, nuts are part of a healthy diet due to their unsaturated fatty acids, dietary fiber, and polyphenols contents (Hosseinpour-Niazi et al. 2021). Indeed, rodent studies showed that beneficial effects of walnuts, almonds, cashews, and pistachios are related to their polyphenols, especially due to their anti-inflammatory and antioxidant properties (Adebayo, Oboh, and Ademosun 2021; Ren et al. 2022; Paterniti et al. 2017; Siracusa et al. 2020; Tedong et al. 2010; He et al. 2022).

Legume consumption was previously associated with lower risk of developing type 2 diabetes and cancer mortality, especially in diabetic and obese men (Becerra-Tomás et al. 2018; Papandreou et al. 2019). Legumes are an alternative protein source to meats in plant-based diets. Studies have shown that replacing red meat or processed red meat with legumes decreases the risk of developing MetS (Becerra-Tomás et al. 2016). The intake of legumes, instead of red meat, reduces the intake of additives, such as nitrates, nitrites, and salt, known to be associated with endothelial dysfunction, impaired insulin response, and hypertension leading to an increased risk of MetS (Pereira et al. 2008; Becerra-Tomás et al. 2016). However, protein quality of legumes may be limited due to protein digestibility and essential amino acid profile. The essential sulfur amino acids (e.g. methionine) in legumes, including chickpeas, are usually lower than the recommended values. We can still obtain adequate essential amino acid intake by combining legumes with cereals, such as rice, which typically contain the recommended amounts of sulfur amino acids (Rafii et al. 2020). The increased intake of dietary fiber and protein by legume consumption may contribute to the benefits of legumes on MetS conditions (Grooms et al. 2013; Te Morenga et al. 2011). However, other studies suggest that legumes are not associated with improvement of human health. Recent studies showed that legume consumption is not associated with type 2 diabetes and MetS (Pearce et al. 2021; Ghosn et al. 2021). Another study showed that total legume and dry beans consumption were positively associated with increased cardiovascular disease mortality, but lentils consumption had an inverse effect (Papandreou et al. 2019). Although more studies are needed to elucidate how legumes affect positively or negatively human health, legumes contain bioactive components (e.g., tannins, phytic acid, protease inhibitors, and lectins) that also can be considered as antinutrients (Figure 3). Although the polyphenols in legumes are known to affect protein digestibility and bioavailability of minerals, they are also correlated with antioxidant properties; for example, the polyphenols in chickpeas were correlated with the antioxidant ability (Kaur et al. 2019). Moreover, chickpeas contain chlorogenic acids and isoflavones (e.g. genistein; Figure 3) that are known to regulate lipid metabolism (Gupta et al. 2017; Ali et al. 2021; Farias-Pereira et al. 2018). Legumes consumption can be considered as part of an ‘healthy’ diet due to their polyphenols and dietary fiber contents, but especially if legumes replace meat in someone’s diet.

Legumes and nuts are common sources of fat-soluble vitamins, including vitamin E (tocopherol; Figure 3), which are associated with reduction of MetS risks (Reboul et al. 2006; Zhang et al. 2022; De Lorenzo et al. 2017; Simunovic et al. 2021). Vitamin E refers to a family that includes four tocopherols and four tocotrienols with different pharmacokinetics, but its main form α-tocopherol has been found to be the most bioavailable form of vitamin E (Asbaghi, Sadeghian, et al. 2020; Reboul et al. 2006). The high intake of vitamin E (≥ 500 mg/day) significantly reduced serum TNF-α, while the supplementation with vitamin E in the form of α-tocopherol was more strongly associated with decreased inflammation markers, including CRP and IL-6 in adults (Asbaghi, Sadeghian, et al. 2020). In another recent meta-analysis, vitamin E supplementation at doses lower than 400 mg/day significantly decreased systolic blood pressure in adults (Emami et al. 2019). A clinical study examining the effect of a high dose of vitamin E on insulin resistance in overweight adults found that a dose of vitamin E of 536 mg/day for 3 months significantly decreased FPG and insulin levels compared to placebo (Manning et al. 2004). However, very high doses of vitamin E may not be effective, or may even be harmful to adults with MetS (Manning et al. 2004; Ward et al. 2007). A randomized, double-blind, placebo-controlled clinical trial found that adults with type 2 diabetes who were given a daily dose of 500 mg α-tocopherol or 500 mg mixed tocopherols for 6 weeks had significantly elevated blood pressure compared to adults who received placebo control (Ward et al. 2007). A meta-analysis of randomized controlled trials investigating the effects of vitamin E on glycemic control concluded that there is not sufficient evidence to support an improvement in FPG, insulin, nor hemoglobin A1c (HbA1c) levels following vitamin E supplementation in adults with type 2 diabetes (Xu et al. 2014). Most of these studies used much higher doses of α-tocopherol, as dietary supplement, than the 15 mg recommended daily dietary dose for adults in the United States. A recent study showed that a Med meal with 12.6 mg of tocopherols reduced postprandial oxidized LDL levels with improvement of inflammation/oxidative molecular markers, in comparison to a Western meal with 4.1 mg of tocopherols (De Lorenzo et al. 2017). Taken together, the intake of vitamin E in Med diet may be more beneficial to MetS patients than very high doses of tocopherols given as dietary supplement.

2.4 Whole-grain cereals

Minimally processed cereals, such as whole wheat, whole rye, and brown rice, are more nutritionally dense, containing more dietary fiber (e.g. β-glucan; Figure 4), vitamins, and minerals, than the refined white cereals (Lu et al. 2014). Cereal processing (milling) removes the nutrient-rich components (bran and germ) leaving mostly digestible carbohydrates from the grain endosperm (Lu et al. 2014). Thus, minimally processed cereals are seen as beneficial to MetS conditions by incorporating dietary fiber and bioactive components in a diet (Bergia et al. 2022; Te Morenga et al. 2011). In Med diet, one to thirteen servings of cereals are eaten daily, consisting of mostly whole-grain cereals (Davis et al. 2015; Ministry of Health and Welfare 1999; Bach-Faig et al. 2011).

Dietary fiber from whole-grain cereals is partially responsible for the improvement of MetS risk factors. The nutritional recommendation is 28 g fiber for a 2000 kcal/day diet and Med diet provides about 33 g of dietary fiber on average (Davis et al. 2015; Grooms et al. 2013). Whole-grain cereals improve MetS risk factors by reducing body weight, fat accumulation, glycemic, and inflammatory responses in humans (Te Morenga et al. 2011; Bergia et al. 2022; Iversen et al. 2022; Iversen et al. 2021; van Trijp et al. 2021; Hoevenaars et al. 2019; Schutte et al. 2018; Musa-Veloso et al. 2018; D. N. Cooper et al. 2017; Suhr et al. 2017; Kristensen et al. 2012). Indeed, women at risk of developing MetS on a high fiber diet (≥ 35 g dietary fiber) had their total body weight, BMI, and fat mass significantly reduced compared to the baseline levels in an 8-week randomized controlled trial (Te Morenga et al. 2011). Dietary fiber reduces the absorption rate of nutrients, including glucose, thus, the whole-grain cereals' effects on postprandial plasma glucose (PPG) levels were reviewed by a meta-analysis study (Musa-Veloso et al. 2018). Although foods with whole-grain cereals in general are more beneficial than the refined cereals, cereals' beneficial effects may be dependent on the cereal type (Musa-Veloso et al. 2018). While brown rice was able to reduce PPG levels compared to white rice, bread with whole wheat flour did not ameliorate glycemic response (Musa-Veloso et al. 2018). Consistently, Med diet with low-glycemic index foods (e.g. brown rice) was more effective in reducing PPG levels than Med diet with high-glycemic index foods (e.g. wholegrain bread) (Bergia et al. 2022). Others have suggested that wholegrain rye, but not wholegrain wheat, reduces body weight in comparison to white wheat (Iversen et al. 2021; Suhr et al. 2017). However, the effects of rye and wheat on PPG levels are still debatable (Iversen et al. 2021; Suhr et al. 2017; Musa-Veloso et al. 2018). In addition to the glycemic effects, fermentation of dietary fiber by the gut microbiota produces short chain fatty acids (e.g. propionate and butyrate) that are linked with improvement of MetS conditions (Iversen et al. 2022; van Trijp et al. 2021; D. N. Cooper et al. 2017). A previous study showed that the dietary fiber intake from wholegrain rye increased levels of propionate and butyrate (Figure 4), which were associated with fat reduction in humans (Iversen et al. 2022). Replacing refined cereals with whole-grain cereals provides dietary fiber, which has shown to be linked to improvement of metabolic parameters. Moreover, vitamins and polyphenols, found more in whole grain cereals than refined cereals, may contribute to beneficial health outcomes in MetS patients (Lu et al. 2014; Zujko et al. 2018).

2.5 Fruits and vegetables

Med diet includes high intake of vegetables and fruits, with daily servings up to nine and three, respectively (Finicelli et al. 2019; Davis et al. 2015; Ministry of Health and Welfare 1999; Bach-Faig et al. 2011). The consumption of fruits and vegetables in Med diet provides dietary fiber, vitamins, minerals, and polyphenols, which are associated with improvement of MetS conditions (Domínguez-López et al. 2021; López-González et al. 2021). Fruits and vegetables are considered nutrient-dense foods with low energy content, thus the increased intake of fruits and vegetables reduces the overall energy intake leading to lower risks of weight gain (A. J. Cooper et al. 2012). Moreover, studies showed that adults who consumed more fruits and vegetables had the lowest risk of MetS and type 2 diabetes, in comparison to groups with lower or insufficient fruits and vegetable intake (Li et al. 2017; A. J. Cooper et al. 2012). In this narrative review, we use examples of fruits and vegetables and their components to discuss their effects on MetS conditions, however it is worth noting that fruits and vegetables may have overlapping and/or different effects on MetS conditions.

Berries are colorful fruits found in red, blue, and purple color with low calories and fat, but high in fiber, polyphenols, and vitamins content (Basu et al. 2021; Calvano et al. 2019). Berry pigments come from their polyphenols, especially anthocyanins, a subclass of flavonoids (Calvano et al. 2019; Aboonabi et al. 2020). Anthocyanins from berries are antioxidant and anti-inflammatory compounds, which help to reduce the risk of MetS and associated diseases, as discussed previously in this current review (Calvano et al. 2019; Aboonabi et al. 2020). A study done on MetS patients showed that a 4-week anthocyanins intervention (320 mg/day, equivalent to 100 g of fresh bilberries) had favorable effects on cardiometabolic risk factors and platelet activity, suggesting that anthocyanins prevent the progression of atherosclerosis in MetS patients (Aboonabi et al. 2020). Previous studies showed that meals with 150 g blueberries decreased type 2 diabetes markers, including postprandial glucose levels after meal challenge up to 24 h (Sobolev et al. 2019; Curtis et al. 2022). Moreover, the daily intake of strawberries or blackberries (about 300-400 g/day) reduced insulin resistance after one to four weeks in overweight and obese adults (Basu et al. 2021; Solverson et al. 2018). Overall, anthocyanins were at least in part associated with improvement of metabolic parameters, including lipid profile, glucose metabolism, and inflammation by berry-rich meals in humans (Sobolev et al. 2019; Curtis et al. 2022; Nilsson et al. 2017; Basu et al. 2021; Solverson et al. 2018).

Citrus fruits (e.g. oranges, lemons, mandarins, and grapefruits) are also part of Med diet and their polyphenols, especially the flavonoids (e.g. naringenin, hesperidin, nobiletin and tangeretin), are linked to improvements of MetS risks (Dayi and Ozgoren 2022). A recent study showed that the flavonoids from citrus peels extract inhibited fat accumulation by decreasing *de novo* synthesis of cholesterol and fatty acids in hepatocytes. Those beneficial effects of citrus flavonoids on lipid profile were dependent on the changes on microbiota in obese mice (Zeng et al. 2020). In humans, the consumption of orange juice, containing 137 mg of vitamin C, 135 mg of hesperidin (Figure 5) and 16 mg of narirutin, was positively associated with reduction of triglycerides after 12 weeks in subjects with higher triglycerides levels at baseline, but overall orange juice did not regulate circulating lipids and insulin sensitivity in overweight and obese people (Simpson, Mendis, and Macdonald

2016). Orange juice consumption was also associated with lower body weight, cholesterol levels, and LDL levels. Men who drank about 236 mL of orange juice per day were 36% less likely to have MetS (O'Neil et al. 2012). However, fresh citrus fruits may be more effective in reducing MetS risks. For example, fresh grapefruit reduced more body weight and insulin levels significantly than grapefruit juice and encapsulated grapefruit after 12 weeks in MetS patients (Fujioka et al. 2006). Although there are other factors to be considered when evaluating the effects of citrus fruits in humans, such as diet quality, citrus fruits have been shown to be beneficial to MetS patients.

Another pigment-related class mostly found in fruits and vegetables that are associated with improvement of MetS is the carotenoids (Beydoun et al. 2019). Carotenoids are tetraterpenoids which are subcategorized into the oxygen-containing xanthophyls (e.g., lutein and zeaxanthin) and carotenes (e.g. β-carotene and lycopene; Figure 5), which are precursor of vitamin A (retinol) (Beydoun et al. 2019). Recent studies examining the association between carotenoids, MetS-associated diseases, and MetS conditions suggest there is an inverse association between carotenoid levels and incidence of MetS (Beydoun et al. 2019; Harari et al. 2020; Matsumoto et al. 2020; Xiao et al. 2019; Yao et al. 2021; Cheng et al. 2019). However, the effects of carotenoids may be gender-specific; serum and skin carotenoid levels significantly correlated with lower BMI, systolic and diastolic blood pressure, HOMA-IR, blood insulin, and triglyceride levels in women, and with lower BMI and blood insulin levels in men (Matsumoto et al. 2020). The strongest associations with MetS were observed for β-carotene, followed by α-carotene and β-cryptoxanthine, and no association observed for retinol, which suggests that carotenoids may act differently on human health (Beydoun et al. 2019). Although these studies suggest that carotenoids found in fruits and vegetables are inversely associated with prevalence of MetS, further interventional studies need to assess the efficacy of carotenoids in treating MetS. The associations for carotenoids may be related to other components in the same food, such as dietary fiber in fruits and vegetables.

Fruits and vegetables are also rich in water-soluble vitamins, such as vitamin C (i.e. ascorbic acid; Figure 5). Much research has been conducted investigating the health benefits of vitamin C, in particular for treating viral respiratory illnesses, cancer, and cognitive function. Here we focus on studies involving vitamin C in the treatment of MetS, which include studies on the improvement of cardiovascular function, glycemic control, and lipid profile. Vitamin C, at doses ranging from 90-4000 mg/day, significantly improved endothelial function in adults with atherosclerosis or diabetes, but no improvement was observed in healthy adults, smokers, or adults with hypertension (Ashor et al. 2014). An 11-year cohort study found that intake of vitamin C is inversely correlated with fatal myocardial infarction or stroke (Martín-Calvo and Martínez-González 2017). However, 6-week oral administration of vitamin C did not alter vascular dilation in adults aged 57-80 years, suggesting short-term treatment with vitamin C does not alter vascular health (Singh et al. 2002). A recent systematic review and meta-analysis shows that vitamin C significantly lowered HbA1c, serum glucose, triglycerides, total cholesterol, and blood pressure in adults with type 2 diabetes (Mason, Keske, and Wadley 2021). However, longer-term and higher quality studies to assess the effects of vitamin C on MetS, since the beneficial effects of vitamin C may not apply to every population. For example, vitamin C significantly reduced glucose levels in adults who were older, more overweight, and/or had higher baseline plasma glucose levels, but vitamin C did not significantly affect glucose levels when all clinical study participants were analyzed together (Ashor et al. 2017). Although vitamin C is essential to human nutrition, it is still unclear whether vitamin C can help the treatment or prevention of MetS. It is likely that vitamin C and other food components act synergistically against MetS conditions, since the daily intake of vitamin C in Med diet (about 200 mg) is lower than most studies investigating only vitamin C (Davis et al. 2015).

3. Conclusions

Studies have shown that Med diet and its plant-based food components (dietary fiber, unsaturated fatty acids, vitamins, and polyphenols) are associated with improvement of MetS conditions. However, the benefits of Med diet on MetS conditions are not exclusively attributable to certain foods and their bioactive component with overlapping mechanisms on human metabolism. Longer randomized clinical trials are still needed to determine the amounts of each component that may be effective on MetS conditions. The Med dietary pattern combines foods (i.e., wine, olive oil, whole-grain cereals, legumes, nuts, fruits, and vegetables) that protect against MetS conditions and is overall more strongly associated with the reduction of health risk than focusing on specific foods and nutrients. Additionally, the effects of plant bioactive compounds are likely dependent on the population, as we reviewed controversial results of their effects on MetS conditions. Epidemiological studies indicate that there are more factors involved in the benefits of Med diet, such as population behavior and lifestyle, but for this review we have focused on the dietary components of Med diet.

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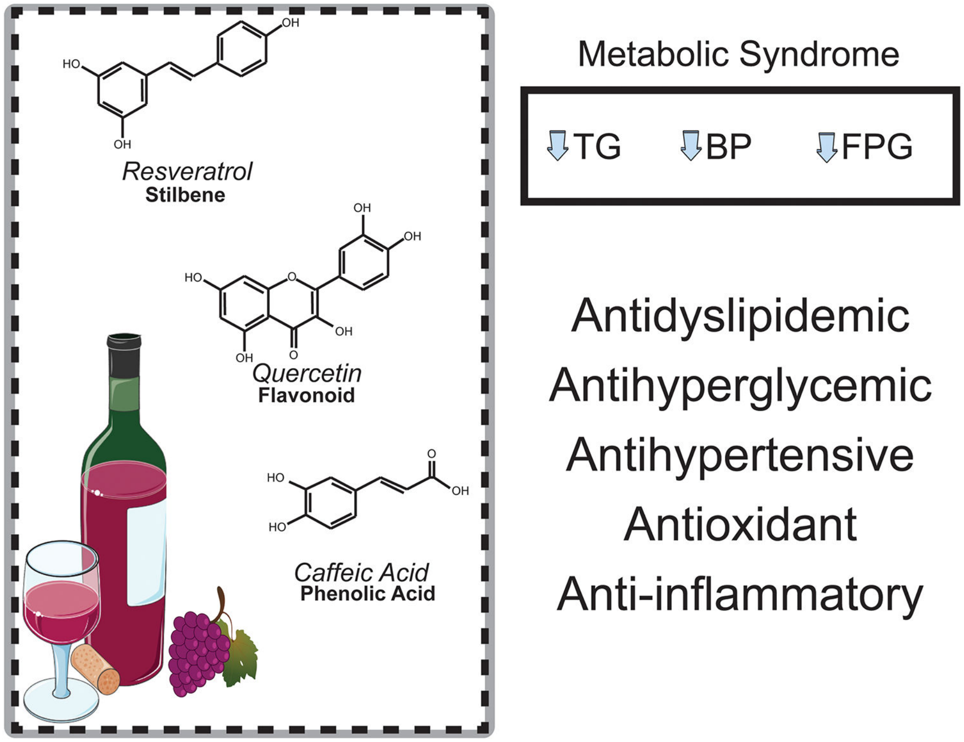

Figure 1.

Red wine and grapes' effects on metabolic syndrome. Moderate consumption of red wine, particularly its polyphenols, has been found to have beneficial effects against metabolic syndrome (Santos-Buelga, González-Manzano, and González-Paramás 2021). Red wine and grape polyphenols can help to reduce fasting plasma glucose (FPG), triglycerides (TG) and blood pressure (BP). However, there is limited evidence regarding their effects on waist circumference and high-density lipoprotein (Asbaghi, Nazarian, et al. 2020; Chiva-Blanch et al. 2013; Lupoli et al. 2020; Mohammad, Shahnaz, and Sorayya 2021; Weaver et al. 2021). Their bioactive compounds, including resveratrol, quercetin and caffeic acid, possess anti-inflammatory and antioxidant properties, which are believed to be the underlying mechanisms behind their positive effects (Gutiérrez-Escobar, Aliaño-González, and Cantos-Villar 2021; Ngamsamer, Sirivarasai, and Sutjarit 2022; Su et al. 2022; Nallathambi et al. 2020). There are still inconsistencies and potential side effects, likely due to the alcohol content of red wine and variations in study methodologies.

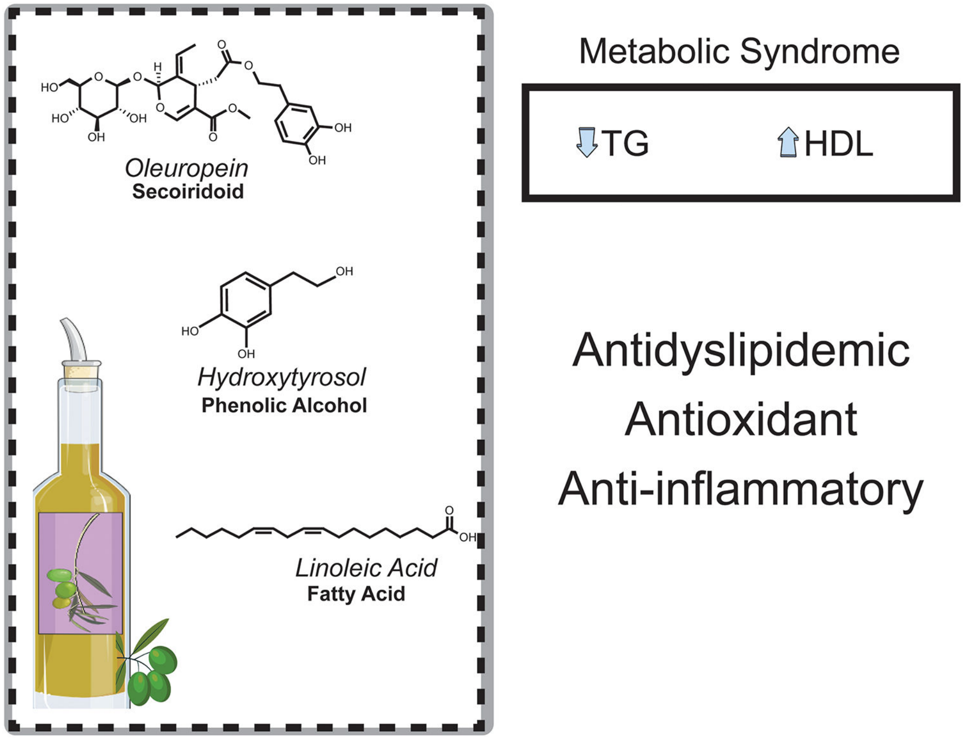

Figure 2.

Olive oil's effects on metabolic syndrome. Extra virgin olive oil is rich in valuable bioactive components such as unsaturated fatty acids (e.g. linoleic acid), secoiridoids (e.g. oleuropein), and phenolic alcohols (e.g. hydroxytyrosol) (Jimenez-Lopez et al. 2020; Rabail et al. 2021). Studies have shown that virgin olive oil can improve triglycerides (TG) levels, increase high-density lipoprotein (HDL) levels, and reduce inflammatory markers, particularly in individuals with metabolic syndrome (Solá et al. 2011; Tsartsou et al. 2019). Animal studies have demonstrated that replacing saturated fatty acids from animal fats with unsaturated fatty acids from extra virgin olive oil can lead to improvements in body weight, lipid profile, and insulin resistance (Zhao et al. 2019; Prieto et al. 2018). Epidemiological and clinical studies suggest that extra virgin olive oil contributes to the effects of the Mediterranean diet on metabolic syndrome. However, it is important to note that these improvements are likely associated with the overall diet rather than solely the consumption of olive oil (Pastor, Bouzas, and Tur 2021; Tsartsou et al. 2019).

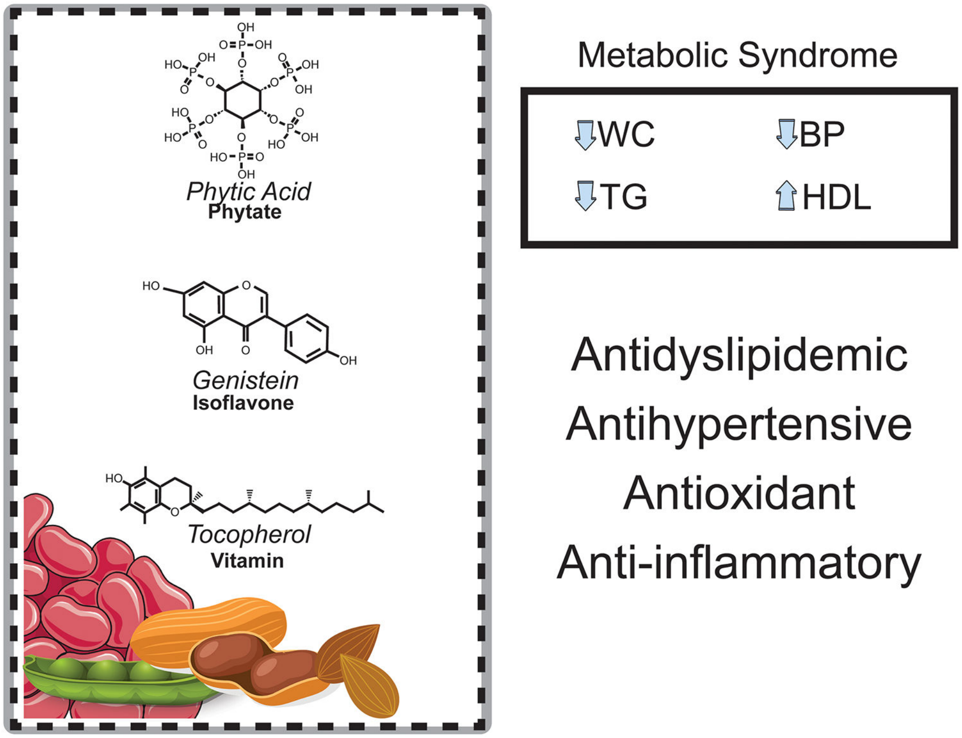

Figure 3.

Nuts and legumes' effects on metabolic syndrome. The beneficial effects of nuts and legumes can be attributed to their protein, unsaturated fatty acids, dietary fiber, fat-soluble vitamins (e.g. tocopherol), and polyphenols (e.g. genistein) content. Consumption of nuts was associated with improvements in metabolic syndrome parameters, including waist circumference (WC), triglycerides (TG) and high-density lipoprotein (HDL) (Julibert et al. 2020). Tocopherol, a form of vitamin E, has been linked to decreased inflammatory markers, systolic blood pressure (BP), fasting plasma glucose (FPG), and insulin levels (Asbaghi, Sadeghian, et al. 2020; Emami et al. 2019; Reboul et al. 2006; Zhang et al. 2022; De Lorenzo et al. 2017). Nuts and legumes also contain antinutrients like phytic acid, which can impact protein digestibility and bioavailability of minerals. However, these antinutrients are also associated with antioxidant properties (Kaur et al. 2019). Overall, the increased intakes of nuts and legumes as part of the Mediterranean diet has been associated with the improvements of metabolic syndrome (Huang et al. 2020; Montemayor et al. 2022; Julibert et al. 2020).

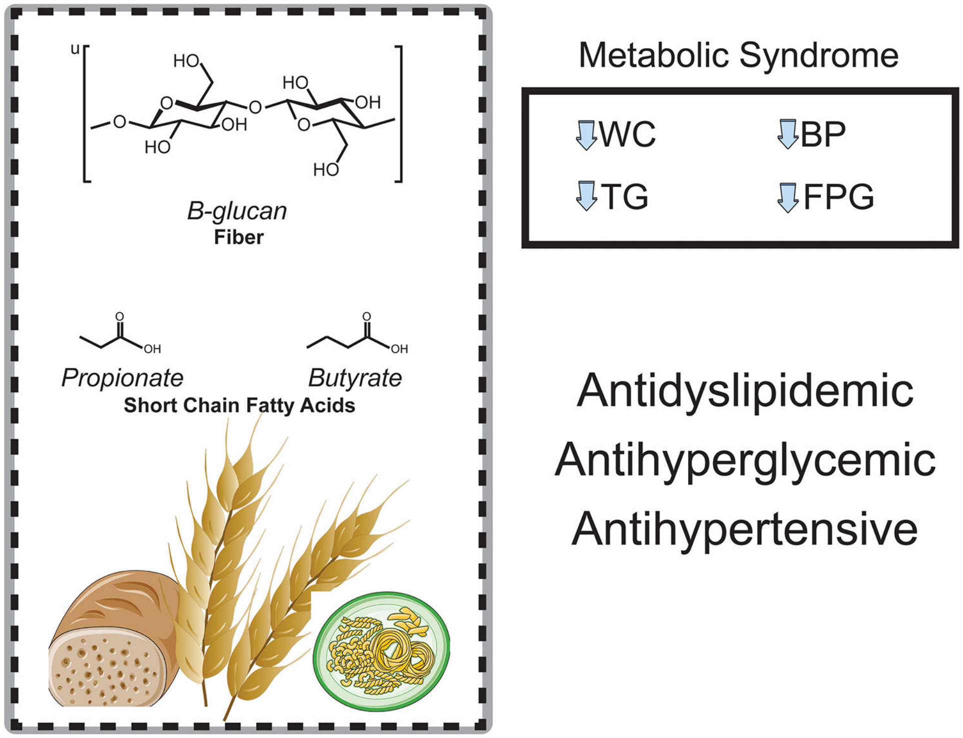

Figure 4.

Whole-grain cereals' effects on metabolic syndrome. Minimally processed cereals are considered beneficial for individuals with metabolic syndrome due to the dietary fiber (e.g. β-glucan) content (Bergia et al. 2022; Te Morenga et al. 2011). Women at risk of developing metabolic syndrome who followed a high-fiber diet (≥ 35 g of dietary fiber) experienced significant reductions in total body weight, waist circumference (WC), fat mass, blood pressure (BP), fasting plasma glucose (FPG), and triglycerides (TG) levels after 8 weeks when compared to the baseline levels (Te Morenga et al. 2011). Dietary fiber plays a role in reducing the absorption rate of nutrients, including glucose, thus demonstrating antihyperglycemic effects (Musa-Veloso et al. 2018). Fermentation of dietary fiber by the gut microbiota produces short chain fatty acids (e.g. propionate and butyrate) that are linked to improvements in metabolic syndrome parameters, including the reduction of overall fat accumulation (Iversen et al. 2022; van Trijp et al. 2021; D. N. Cooper et al. 2017). Whole-grain cereals contain higher levels of vitamins and polyphenols compared to refined cereals, and these components may contribute to the beneficial health outcomes observed in individuals with metabolic syndrome (Lu et al. 2014; Zujko et al. 2018).

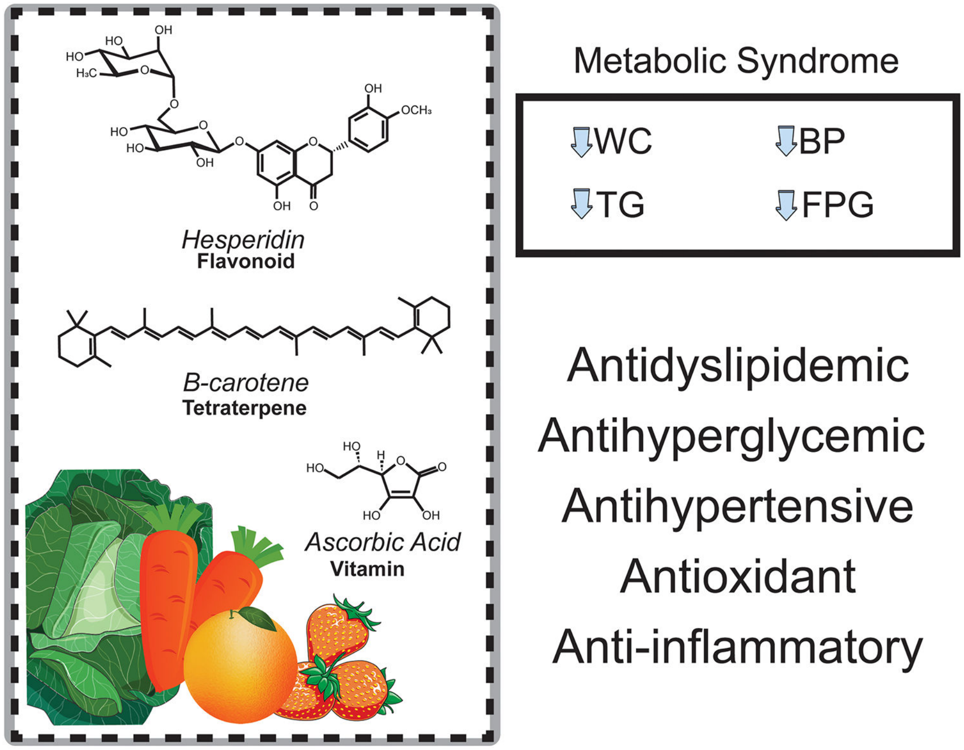

Figure 5.

Fruits and vegetables' effects on metabolic syndrome. The consumption of fruits and vegetables has been associated with a reduced risk of metabolic syndrome (Li et al. 2017; A. J. Cooper et al. 2012). These foods contain multiple components that contribute to their beneficial effects. For instance, berries and citrus fruits are rich in flavonoids, and their antioxidant and anti-inflammatory properties are associated with improvements in metabolic parameters, including high-density lipoprotein (HDL) levels, glucose metabolism, and inflammation (Sobolev et al. 2019; Curtis et al. 2022; Nilsson et al. 2017; Basu et al. 2021; Solverson et al. 2018; O'Neil et al. 2012). Orange juice, which contains vitamin C (ascorbic acid) and hesperidin, has been positively linked to a reduction in triglycerides (TG) levels after 12 weeks (Simpson, Mendis, and Macdonald 2016). Vitamin C has also shown to lower HbA1c, fasting plasma glucose (FPG), and blood pressure (BP) in adults with type 2 diabetes (Mason, Keske, and Wadley 2021). Fruits and vegetables are also a source of carotenoids, such as β-carotene, which have been correlated with lower body mass index and insulin levels (Matsumoto et al. 2020; Beydoun et al. 2019). Overall, the consumption of fruits and vegetables, particularly those rich in flavonoids and vitamins, can contribute to the improvement of metabolic syndrome risk factors.