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Effects of the low-carb organic Mediterranean diet on testosterone levels and sperm DNA fragmentation

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ABSTRACT

The causes of male infertility can vary. Lifestyles, environmental factors, stressful conditions, and socio-economic conditions are significant factors. Diet plays a crucial role in improving a man's reproductive capacity. The appropriate diet should be diverse and ensure the intake of all the necessary nutrients to enhance sperm quality. The Mediterranean diet, which includes high amounts of vegetables and fruits rich in detoxifying and antioxidant substances, as well as polyphenols, flavonoids, carotenoids, and microelements, especially when consumed with organic foods and a lower carbohydrate regimen, are the key aspects addressed in this study. The objective of this research was to modify the diets of 50 subfertile men by providing them with a specific nutritional plan. This plan included consuming 80% organic foods, introducing whole grains and low glycemic load options, eliminating refined carbohydrates, consuming green leafy vegetables and red fruits daily, reducing or eliminating dairy products, consuming primarily grass-fed meat and wild caught seafood, eliminating saturated fats in favor of healthy fats like olive oil, avocado, and nuts. After three months of adhering to the low-carb food plan, testosterone levels significantly increased, while sperm DNA fragmentation decreased in a subgroup of individuals who reduced their carbohydrate intake by 35%.

1. Introduction

Couple infertility is defined as the inability to conceive after more than a year of unprotected sexual intercourse in the absence of other reproductive pathologies (Barratt et al., 2017). The incidence of this condition is increasing, to the extent that it affects 8–12% of couples globally, with the male factor contributing approximately 50% (Agarwal et al., 2021). There can be numerous causes of male infertility. In addition to subjective factors, unhealthy lifestyles and exposure to environmental toxins can also impact a man's reproductive capacity. In particular, continuous exposure to endocrine disruptors chemicals (EDCs) (Yilmaz et al., 2020), a highly diverse group of molecules that includes synthetic chemicals used in industrial solvents/lubricants and their by-products, can lead to adverse reproductive outcomes such as decreased sperm quality and quantity, as well as testicular damage (Chiang et al., 2017; Selvaraju et al., 2021; Fathi Najafi et al., 2015; Pironti et al., 2021, 2023). Unhealthy lifestyle factors, such as smoking cigarettes, alcohol consumption, drug use, coffee intake, lack of sleep, exposure to electromagnetic fields, psychological stress, and poor dietary practices (Durairajanayagam, 2018), as well as being overweight or obese, are more commonly associated with male infertility. These factors can cause hormonal imbalances, as well as direct changes to sperm function and molecular composition (Palmer et al., 2012; Bellastella et al., 2019; Hammoud et al., 2008). In this regard, testicular steroidogenesis plays a fundamental role in production of testosterone and maintaining germ cell development. These functions are supported by two types of somatic cells found in the testes: Leydig cells and Sertoli cells (SCs). Leydig cells are responsible for the production of testosterone.The level of testosterone undergoes dynamic changes during different stages of development. It increases towards the end of fetal life, decreases after birth until puberty, and then increases again. Testosterone exerts its effects through both classical and non-classical

Abbreviations: DFI, DNA fragmentation index; Low-carb diet, Low Carbohydrate Diet.

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mechanisms (Shah et al.). Additionally, it plays a role in the hormonal control of apoptosis in the testis (Sinha Hikim and Swerdloff, 1999). Apoptosis is one of the factors contributing to sperm DNA fragmentation. Low testosterone levels, in combination with other factors such as high levels of reactive oxygen species (ROS), particularly in obese men, are associated with elevated levels of DNA fragmentation index (DFI). (Kahn and Brannigan, 2017).

Generally, when it comes to dietary aspects and eating habits, especially for couples trying to conceive, there is still little attention from clinicians and a lack of clear guidelines. However, there is no doubt that the Mediterranean diet is universally recognized as the most beneficial for maintaining overall health. This diet is characterized by a high consumption of vegetables, fruits, olive oil, grains, dairy products, and nuts, with very low intake of red meat and moderate consumption of fish and wine. Presently, all the most important and influential scientific societies in the world recommend the Mediterranean diet as the ideal dietary profile for maintaining a healthy state and reducing the incidence of major chronic diseases (Guasch-Ferré and Willet, 2021). When it comes to the effects of this diet on sperm quality and male fertility, there are only a few observational studies reported in the literature, and only two randomized controlled trials (RCTs) showing improvements in seminal parameters. One of these studies, conducted by Montano et al., even took place in highly polluted areas and showed improvement in seminal redox status as well (Cao et al., 2022; Caruso et al., 2020; Montano et al., 2021). Recent advancements in understanding the molecular basis of the Mediterranean diet's effects have focused primarily on cardiovascular disease, but also discuss other related diseases. These advancements have reviewed the composition of the Mediterranean diet and the latest developments in evaluating its effects on a genomic, epigenomic (DNA methylation, histone modifications, microRNAs, and other emerging regulators), transcriptomic (selected genes and whole transcriptome), metabolomic, and metagenomic level.

In the literature, a review of the clinical effects of this dietary style and its biochemical and molecular effects has also been reported, highlighting its benefits on human health, particularly its anti-inflammatory, antioxidant, and anti-atherosclerotic effects. Recently, new knowledge on the relationship between epigenetics and gut microbiota has also been added to these effects (Tuttolomondo et al., 2019). It is important to note that adherence to this type of diet, characterized by high intake of vegetables, fruits, and seafood, which are rich in detoxifying and antioxidant substances, can be useful in balancing the production of reactive oxygen species (ROS) and epigenetic alterations caused by environmental contaminants (Chung, 2017; Vanduchova et al., 2019; Chang et al., 2018; Jamalan et al., 2016; Tedesco et al., 2020; Huetos et al., 2019; Ricci et al., 2019; Karayiannis et al., 2017a; Montano et al., 2017; Montano et al., 2022). The consumption of typical foods of the Mediterranean diet is characterized by the consumption of organic foods, which are free of pesticides that have negative effects on human health (Kim et al., 2017; Roeleveld and Bretveld, 2008). Organic foods have higher concentrations of antioxidants and trace elements (Yu-Han Chiu et al., 2016; Barański et al., 2014; Ribes-Moya et al., 2020; Hallmann et al., 2019; Benbrook et al., 2013; Palupi et al., 2012; Średnicka-Tober et al., 2016a), increased levels of omega-3 fatty acids in organic dairy products (Prandini et al., 2009), and higher concentrations of polyunsaturated fatty acids such as omega-3, as well as improved profiles of saturated fatty acids such as linoleic acid and palmitoleic acid in organic meat (Ribas-Agusti et al., 2019; Średnicka-Tober et al., 2016b). Therefore, the higher content of bioactive compounds in organic food compared to conventional ones represents an additional safeguard against the effects of environmental pollutants and helps maintain good general and reproductive health (Hurtado-Barroso et al., 2017a; Vigar et al., 2019a; Montano et al., 2022). However, data suggests that adherence to a "healthy" diet that is rich in certain nutrients such as omega-3 fatty acids, antioxidants (vitamin E, vitamin C, β-carotene, selenium, zinc, and lycopene), and other vitamins (vitamin D and folate), while low in saturated and trans fatty acids, can help improve some semen quality parameters, particularly those related to sperm motility, which is one of the most important parameters for fertility (Chiu et al., 2015; Safarinejad et al., 2010; Salas-Huetos et al., 2019a). Additionally, it may also improve sperm DNA fragmentation index (Karayiannis et al., 2017b). Sperm cells are particularly sensitive to endogenous and exogenous stress, including oxidative stress, which is the final effect of a series of intracellular events triggered by insult (Gallo et al., 2020; Montano et al., 2018; Bergamo et al., 2016). Sperm DNA is also an excellent indicator of male fertility, as even if other sperm parameters may be normal, high DNA fragmentation can be the main cause of undiagnosed/unexplained infertility. Furthermore, pollutants seem to have DNA damage as their primary effect, thus any antioxidant dietary intervention is important for maintaining genomic integrity (Rubes et al., 2005; Bosco et al., 2018; Aitken et al., 2009).

In this study, we focused on the organic Mediterranean diet, particularly on a low-carb regimen. Apart from promoting weight loss, this regimen is effective in stabilizing blood sugar levels and has beneficial effects such as reducing the risk of type 2 diabetes and metabolic syndrome (Westman and Yancy, 2020). In general, low-carb diets limit the intake of carbohydrates to less than 130 g per day or less than 45% of total calorie intake, while favoring the consumption of low-glycemic index carbohydrates. The main hypothesis behind low-carb approaches is that reducing insulin, a critical hormone that promotes fat storage, improves cardiometabolic function and induces weight loss (O'Neill, 2020). Studies have shown that a moderately low-carb diet can be beneficial for the heart, as long as the protein and fat come from healthy sources (O'Neill, 2020). Higher-carb foods such as fruits, starchy vegetables, and whole grains can also be included in these diets in moderation (O'Neill, 2020).

2. Material and methods

2.1. Subjects

The nutritional aspects of 50 men who turned to a pre-conception diet, with an age ranging between 35 and 45, were evaluated from November 2020 to October 2021.

2.2. Measures

Adherence to the Mediterranean diet (MD) was evaluated using a 15-item food frequency questionnaire, which has already been validated to assess adherence to the Mediterranean dietary pattern among Italian adults, scoring from 0 (minimal adherence) to 9 (maximal adherence) (Biasini et al., 2021). Anthropometric measurements were taken for the male participants, and only those with a body mass index (BMI) ranging from 20 to 24 were included in the evaluation. The selection criteria for the EcoFoodFertility project, a human biomonitoring study investigating the impact of pollutants, diet, and lifestyle on reproductive and overall health, led to the exclusion of patients who were smokers, habitual drinkers, obese, underweight, had varicocele, or had chronic pathologies. Further details about this project can be found at https://www.ecofoodfertility.it/(accessed on July 12, 2022). All methods employed in this study were conducted in accordance with the World Medical Association Code of Ethics Guidelines (Declaration of Helsinki) and regulations. The baseline characteristics of the study population are presented in Table 1.

2.3. Material & methods

After obtaining informed consent, a group of 50 individuals were assigned a Mediterranean diet regimen consisting of the following precise nutritional guidelines:

Consumption of 80% organic foods.

Daily intake of whole grains and foods with a low glycemic index.

Table 1
Characteristics of the study population.

Variables	mean ± SEM
Age (yr)	40,2 ± 0,9
Body measurements	
Weight (kg)	75,5 ± 1,3
Height (mt)	1,8 ± 0,01
BMI (kg/m2)	23,8 ± 0,3
Adherence to the Mediterranean Diet score (on a 0–9 scale)	3,02 ± 0,2
Semen parameters	
Volume (ml)	2,6 ± 0,2
Sperm concentration (106/ml)	32,9 ± 4,9
Total motility (%)	31,03 ± 4,9
Progressive motility (%)	10,15 ± 1,4
Cell with normal morphology (%)	3,38 ± 0,3

Age, body measurements, adherence to the Mediterranean Diet score and semen parameters, including spermiogram variables, are reported as mean ± SEM. SEM = standard error of the mean.

Breakfast included whole grain bread with a protein source like eggs, wild salmon, nuts, and red fruits. Alternatively, oats in the form of pancakes or porridge were also allowed as a breakfast option.

Dairy products were eliminated or reduced, with some exceptions for goat cheeses.

Daily consumption of fermented foods such as yogurt or kefir.

Daily consumption of red fruits.

Daily consumption of 3 portions of green leafy vegetables.

Daily consumption of 30 g of nuts.

Consumption of legumes at least 3–4 times a week.

Consumption of wild-caught seaweed at least 5–6 times a week, including oily fish 2–3 times.

Elimination of processed meat.

Consumption of grass-fed or organic meat 3–4 times a week.

Consumption of 8–10 eggs per week.

Fruit consumption limited to a maximum of 300 g per day.

Consumption of cruciferous vegetables at least 4–5 times a week.

Elimination of packaged products.

Frequent use of spices such as ginger, turmeric, coriander, rosemary, basil, garlic, onion, and parsley.

A subgroup of 20 participants out of the initial 50 were given additional instructions to reduce their carbohydrate intake to 35% of their daily caloric intake.

The participants adhered to the diet for a period of 3 months before undergoing a testosterone test and Sperm DNA fragmentation test.

2.4. Blood analysis

The participants underwent blood chemistry tests at their designated laboratory.

2.5. DNA fragmentation index (DFI)

Participants were instructed to abstain from sexual activity for a minimum of two days and a maximum of five days before providing a semen sample on-site. The DFI analysis was then conducted at their designated laboratory using the Sperm Chromatin Dispersion (SCD) test (Fernández et al., 2003; Bosco et al., 2018). In brief, the semen samples were diluted in a 1 × phosphate buffered saline solution (PBS Gibco, Invitrogen) with a pH of 7.4 to avoid overlap of sperm DNA halos. Semen samples with a sperm concentration below 10 × 106/mL were not diluted. A portion of the semen sample was embedded in low melting point agarose and spread onto an agarose pretreated slide using the Halosperm® kit (Halotech DNA SL Spain). A total of 500 spermatozoa were observed for each sample using brightfield microscopy (Nikon Ci-L) and categorized based on the size of the sperm DNA dispersion halo. Five different patterns of sperm DNA halos were observed: large and medium, categorized as non-fragmented DNA, and small, absent halos, and degraded spermatozoa, categorized as fragmented. The DNA fragmentation index (DFI) values were calculated as the percentage of fragmented nuclei relative to the total number of cells. Fig. 3 illustrates the interpretation of the sperm chromatin dispersion test (SCD) and was captured using a Gigabit Camera (Basler Ace ACA780-75 GC) connected to the microscope.

3. Data analysis

The data from each group are presented as the mean ± SEM. Statistical significance was determined using an unpaired two-tailed *t*-test, with values considered significantly different if $p < 0.05$. $P < 0.05$; $^{*}P < 0.005$. The unpaired two-samples *t*-test is utilized to compare the means of two independent groups and determine if there is a significant difference between them.

4. Results

In total, the dietary habits of 50 male participants were assessed, along with the impact of dietary changes on their testosterone levels and Sperm DNA fragmentation. An examination of their eating habits revealed a consumption of low-quality proteins, excessive intake of high glycemic index and refined carbohydrates, as well as sweet foods. Moreover, they exhibited limited concern for food quality, rarely reading food labels, and rarely purchasing organic products. Many participants consumed excessive amounts of coffee and processed foods, including dairy products.

Following nutritional counseling and the implementation of a personalized dietary plan, it was observed that individuals who modified their diet by reducing refined sugars and increasing their consumption of whole grains, fresh vegetables, and legumes, while avoiding packaged foods and dairy products, experienced a noteworthy increase in testosterone levels ($p < 0.05$, $n = 30$) (Fig. 1).

Simultaneously, the group of men who adhered to a diet comprising approximately 50% carbohydrate intake for 3 months ($n = 20$), whereby their antioxidant intake was increased through daily consumption of red fruits and a minimum of 3 portions of fresh vegetables per day, while avoiding packaged foods and eliminating dairy products, demonstrated a notable reduction in sperm DNA fragmentation ($p < 0.005$) ($n = 20$) (Fig. 2).

5. Discussion

The present study demonstrates the beneficial effects of a diet rich in

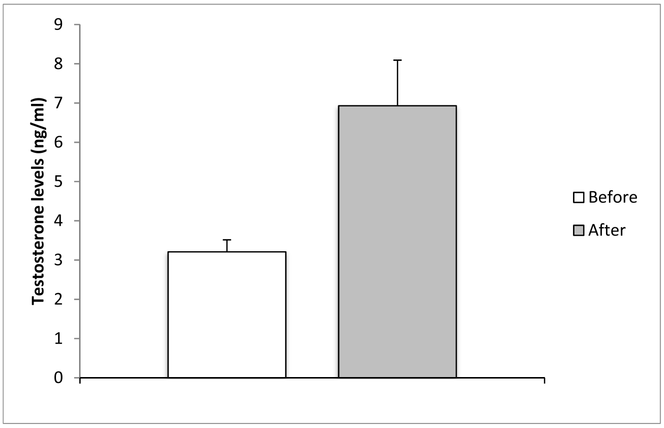

Fig. 1. Evaluation of testosterone levels following a 3-month period of dietary modifications. The "Before" value represents the baseline level before commencing the diet, while the "After" value indicates the level after 3 months of diet. The statistical analysis revealed a significant difference ($p = 0.011$; $p < 0.05$). The initial testosterone level was 3.2 ± 0.3, whereas after the diet it increased to 6.92 ± 1.16.

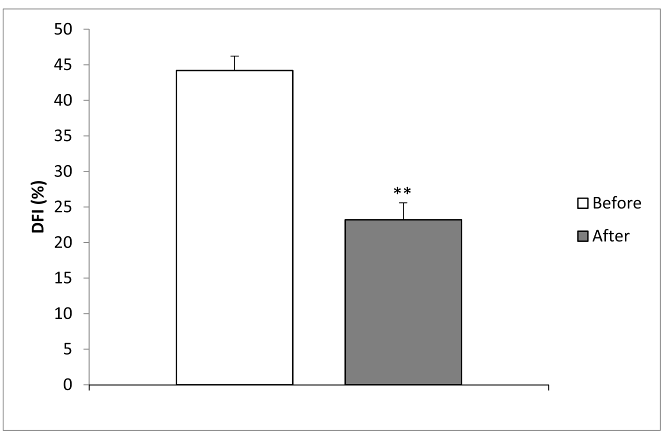

Fig. 2. Evaluation of DFI levels after 3 months of dietary intervention. "Before" represents the baseline value prior to initiating the diet, while "After" signifies the value after 3 months of adhering to the prescribed dietary plan ($p = 0.001$; $p < 0.005$). The initial DFI level was recorded as 44.2 ± 3.02, whereas after the intervention, it declined to 23.2 ± 3.57.

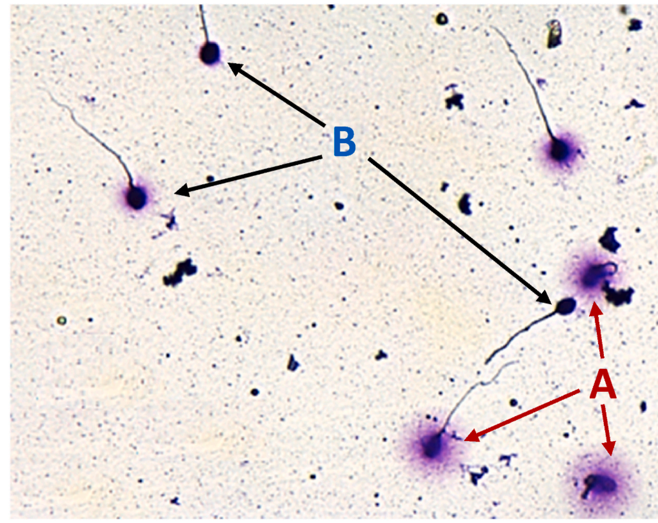

Fig. 3. Interpretation of the SCD test. Interation of the SCD test: Spermatozoa that are not fragmented are denoted as A, while spermatozoa with fragmented DNA are denoted as B.

antioxidant and detoxifying foods, polyunsaturated fats, and whole grains on two male fertility parameters: testosterone levels and sperm DNA fragmentation. Our findings indicate that men who adhere to the Mediterranean diet and reduce their carbohydrate intake experience lower sperm DNA fragmentation and increased testosterone levels. Previous studies have also shown an inverse correlation between serum testosterone levels and energy intake of carbohydrates and proteins (Volek et al., 1985). Glucose loading has been found to reduce total and free testosterone levels, potentially due to changes in insulin resistance (Caronia et al., 2013). Long-term changes in protein and carbohydrate intake can impact testosterone metabolism and indirectly affect weight and visceral adiposity. The authors propose two hypotheses: 1) that testosterone levels might decrease as a result of insulin's inhibitory effect on hepatic SHBG production; 2) the reduction in testosterone might be influenced by peripheral signals to the central nervous system, such as leptin, which could impact the HPG (hypothalamic-pituitary-gonadal) axis and lead to a disruption in communication. Both insulin and leptin play crucial roles in transmitting information to the brain regarding energy reserves, consequently affecting hormonal balance.

Another study conducted on young athletes in 2017 (Wilson et al., 2020) showed that following a ketogenic diet led to increased total testosterone levels compared to a Western-style diet. This could be attributed to the higher concentration of cholesterol in a ketogenic diet, which serves as a precursor for sex hormone production.

High levels of Reactive oxygen species (ROS) are responsible for a significant percentage of male infertility cases, in fact they can damage sperm DNA, membranes, and proteins (Agarwal and Said, 2005). Lifestyle factors such as obesity, stress, alcohol, tobacco, environmental factors like heat and pollution, and inflammation increase the risk of ROS generation (Tremellen, 2008). When the amount of ROS exceeds the sperm's ability to scavenge them, oxidative stress occurs, resulting in impaired sperm motility, membrane damage, DNA sperm damage and even apoptosis (Gharagozloo and Aitken, 2011; Sharma and Agarwal, 1996; Agarwal et al., 2008; Lee et al., 1997). Spermatozoa are highly susceptible to oxidative damage owing to the abundance of polyunsaturated fatty acids (PUFA), which pose a high risk of lipid peroxidation (Wathes et al., 2007). Furthermore, during the maturation process of sperm, there is a decrease in cytoplasmic content (Wathes et al., 2007; Flesch and Gadella, 2000), resulting in reduced levels of enzymes and antioxidants required to counteract reactive oxygen species (ROS) production and repair ROS-induced nuclear and mitochondrial DNA damage (Lee et al., 1997).

It is crucial to consume vitamins and antioxidants through diet to protect sperm from oxidative damage. Seminal plasma contains enzymatic antioxidants such as SOD, catalase, and glutathione peroxidase (Mennella and Jones, 1980; Zini et al., 1993; Vernet et al., 2004), as well as non-enzymatic antioxidants like vitamin C, vitamin E, carotenoids, and flavonoids (Gharagozloo and Aitken, 2011). Non-enzymatic antioxidants can be obtained through dietary intake and act synergistically with enzymatic antioxidants to eliminate ROS.

Certain foods and nutrients have stronger associations with fertility benefits. It is essential to maintain a healthy weight and pay attention to nutrition to promote good sperm quality (Oostingh et al., 2017). Diets high in refined carbohydrates and sugar have negative effects on sperm health, including reduced motility, morphology, and count (Cutillas-Tolin et al., 2019; Danielewicz et al., 2018). A Mediterranean-type diet, which includes fruits, fish, vegetables, legumes, whole grains, healthy fats, and oils, has been shown to improve male fertility (Guasch-Ferré and Willet, 2021; Salas-Huetos et al., 2019b). Increasing the consumption of green leafy vegetables and cruciferous vegetables aids liver function and has anti-inflammatory effects (Gaskins et al., 2012). Protein intake also plays a role in sperm morphology and motility, and improving the oxidative state can be achieved by decreasing carbohydrate intake and increasing protein intake (Ajuogu et al., 2020; Xia et al., 2015; Harris et al., 2011).

DNA fragmentation is a significant factor in male infertility (Nassan et al., 2018). High levels of DNA fragmentation decrease the chances of natural conception or success with procedures such as intrauterine insemination and in vitro fertilization. Minimizing DNA fragmentation is crucial, as oxidative stress is the primary cause. Antioxidants can protect against oxidative stress and potentially improve conception rates. Fruits and vegetables are rich in antioxidants, such as vitamin C, vitamin A, β-carotene, polyphenols, minerals like potassium and magnesium, folate, and fiber.

There is a direct correlation between antioxidant status and the generation of reactive oxygen species (ROS) in spermatozoa (Ross et al., 2010). The Mediterranean diet, which is rich in antioxidants and essential vitamins for sperm function, such as coenzyme Q-10, plays a crucial role in sperm motility by facilitating movement and energy release in sperm. Vitamins B aid in liver detoxification and the elimination of free radicals, promoting healthy sperm growth and assisting in protein synthesis and division. Folate (vitamin B9) and vitamin B12, concentrated in the sperm head, provide essential nutrients for sperm production and survival (Azizollahi et al., 2013). Folate deficiency, commonly found in green leafy vegetables, is associated with apoptosis through p53. Folate-deficient cells have significantly increased lipid peroxidation indices, activating a redox-sensitive transcription factor, NF-κB, responsible for reactive oxygen species-mediated apoptosis (Murphy et al., 2011). Vitamin C, abundant in citrus fruits, is necessary for the development of healthy sperm cells (Akmal et al., 2006). The Mediterranean diet, rich in essential fatty acids, is crucial for sperm health, especially omega-3 fatty acids like docosahexaenoic acid (DHA). DHA, found mainly in the sperm tail, is associated with motility and the sperm's ability to fertilize the oocyte. Low levels of DHA are linked to an increase in abnormal sperm forms (Aksoy et al., 2006). Additionally, various phytochemical compounds found in the Mediterranean diet have been found to interact with contaminants, offering protection against their harmful effects through mechanisms such as scavenging ROS, chelation of toxic metals, anti-inflammatory action, and epigenetic up-regulation of detoxifying genes or enzymes (Chung, 2017; Vanduchova et al., 2019; Chang et al., 2018; Jamalan et al., 2016; Tedesco et al., 2020; Montano et al., 2022). Adhering to a diet rich in antioxidants can help improve semen quality and counteract the negative impact of contaminants, including dangerous pesticides and phthalates (Montano et al., 2021; Kelly, 2004). Organic food, known for its higher content of bioactive compounds and lower levels of nitrates, Cadmium, pesticides, fertilizer, and pollutants, has been shown to improve various health outcomes, including fertility treatment, overweight and obesity reduction, prevention of pre-eclampsia in pregnancy, eczema in infants, some cancers, diabetes, and other noncommunicable diseases (Hurtado-Barroso et al., 2019; Liang et al., 2019; Glibowski, 2020; Baudry et al., 2018; Chiu et al., 2018; Sun et al., 2018; Bradman et al., 2015a; Curl et al., 2019a). The lower morbidity associated with organic food consumption is believed to be due to reduced exposure to pesticide residues and increased intake of antioxidants; however, more research is needed to draw a definitive conclusion (Hurtado-Barroso et al., 2019). A large-scale randomized clinical trial comparing the effects of organic and conventional products on human health, lasting more than 4 weeks, has not yet been conducted. Recommendations have been made to conduct such studies to provide solid evidence on the benefits of organic food (Glibowski, 2020; Hurtado-Barroso et al., 2017b; Vigar et al., 2019b).

Given that enhancing male fertility requires addressing lifestyle factors (Humaidan et al., 2022), the findings presented in this study underscore the positive effects of dietary variation and the incorporation of organic foods on male fertility. Organic foods, which accounted for approximately 80% of the participants' diet, have been found to enhance the antioxidant capacity of the Mediterranean diet. Furthermore, studies have indicated that an organic diet is associated with decreased levels of urinary pesticide analytes, including glyphosate, a widely used herbicide (Bradman et al., 2015b; Curl et al., 2019b; Fagan et al., 2020). However, investigations on the protective effects of organic food against pollutant toxicity are still lacking, although there are studies that report the effects of single substances with the ability to detoxify the body from environmental pollutants (Chung, 2017; Vanduchova et al., 2019; Chang et al., 2018; Jamalan et al., 2016; Tedesco et al., 2020).

6. Conclusions

The male contribution to a couple's fertility is important and the findings of this study underscore the importance of dietary variation and the inclusion of organic foods in achieving this goal. Specifically, adhering to a pre-conception Mediterranean diet that is low in carbohydrates and high in legumes, whole grains, and green leafy vegetables, along with consuming 80% organic foods, was associated with improved testosterone levels and reduced sperm DNA fragmentation. Although this study has a limited sample size and is currently being expanded, it emphasizes the significance of consuming quality food for physical and psychological well-being, and suggests that it may serve as an achievable measure of human resilience against environmental insults.

CRediT authorship contribution statement

Veronica Corsetti: Conceptualization, Investigation, Methodology, Software. **Tiziana Notari:** Visualization, Investigation. **Luigi Montano:** Conceptualization, Data curation, Writing – original draft, preparation, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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