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Challenges and future perspectives of sustainable supplements, functional foods, and nutrigenomics in athletic performance

review paper
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ABSTRACT

Nutrition plays a key role in the lives of athletes, sustaining and enhancing sports performance by significantly influencing their performance and general well-being. Functional foods, rich in bioactive compounds and essential nutrients, offer significant advantages for general health and athletic performance. This review addresses the benefits of sustainable, functional foods for health and sporting needs and the strategies to improve sustainability in the food sector. It will explore the connection between sustainable nutrition, nutrigenomics, and sporting needs. Sustainable food offers several advantages over traditional supplements. Thus, it is essential to educate consumers about the environmental impact of conventional supplement production and the benefits of sustainable options. The necessary approach must be integrated into food production, distribution, and consumption to meet current nutritional needs. Incorporating sustainability into supplement production and using functional foods to formulate supplements will be explored to point out the advantages of sustainable foods over traditional supplements. This review underscores the importance of public awareness and education in adopting sustainable eating habits, utilizing what nature offers more consciously, and implementing these principles in daily life. The importance of food sustainability is underscored by its impact on climate change and global health, as food production contributes significantly to greenhouse gas emissions. Addressing this involves improving diet quality while reducing the environmental footprint of food production. Through these efforts, functional foods can serve as a key component in achieving sustainable sports supplementation, benefiting individuals and the planet.

Key words: nutrition, sport, food sustainability, human health, environmental impact

Introduction

Importance of food sustainability

Food waste is a critical and pressing issue for a world struggling with the effects of climate change [1]. The urgency of addressing food sustainability is evident, as our global food system is responsible for 34% of anthropogenic greenhouse gas emissions. Agriculture and changes in land use contribute the most to these emissions, accounting for 71% [2, 3]. These factors severely impact the planet and, consequently, global health. Significant challenges lie in improving diet quality while simultaneously reducing the environmental impact of the food production chain. This involves addressing current gaps in understanding nutrient waste and implementing various sustainability measures [4]. One of the Food and Agriculture Organization of the United Nations' (FAO's) areas of intervention is food sustainability. According to the organization, sustainable food and agriculture contribute to the four pillars of food security: availability, access, utilization, and stability. It will be essential to raise public awareness about sustainable eating habits, the value of our natural resources, and the need to reduce food waste.

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The necessary approach must be integrated into food production, distribution, and consumption, aimed at meeting current nutritional needs. This broad concept therefore includes various aspects: environmental sustainability [5], economic sustainability [6], social sustainability [7], health and well-being [8], and waste reduction [1]. Overall, food sustainability requires a collective commitment from governments, industries, farmers, consumers, and other stakeholders to create a resilient and equitable food system. Various environmental insults, such as the use of detergents, disinfectants, microplastics, nanoparticles, and tobacco, have a significant negative impact on global health. Dietary changes, marked by increased consumption of ultra-processed foods rich in emulsifiers, further exacerbate these adverse effects [9]. In this complex scenario, it becomes imperative to implement changes in government systems that create a comprehensive network involving all levels of the food production chain, from farmers to consumers. Urgent policy measures are needed to raise farmers' awareness of the risks posed by climate change, and it is necessary to raise public awareness about sustainable eating habits, the value of our natural resources, and the urgency of reducing food waste [10, 11].

The purpose of this review is to illustrate how sustainability can be applied to sports nutrition by studying the scientific landscape and integrating the concept of functional food and nutrigenomic for a sustainable approach to sports supplementation. Additionally, it aims to raise public awareness on how the concept of sustainability can be applied and implemented in everyday life, by making more conscious use of what nature already provides.

Material and methods

Literature search

This review was conducted through a comprehensive search of the scientific literature in databases such as PubMed, Scopus, and Google Scholar. The search focused on peer-reviewed articles, review papers, and relevant reports published within the last 25 years. Key search terms included "sustainability," "sports nutrition," "functional foods," "food sustainability," "nutrigenomics," "athletic performance," and "sustainable diets." The inclusion criteria required studies to focus on the intersection of sustainability and sports nutrition, particularly those discussing the role of functional foods in enhancing athletic performance and promoting sustainable food systems.

Studies were included if they met the following criteria:

– Published in English.

– Provided data or theoretical analysis on the impact of functional foods on athletic performance.

– Discussed the environmental, economic, and social aspects of food sustainability.

– Included assessments or models relevant to integrating sustainability into sports nutrition.

Studies were excluded if they:

– Focused solely on general nutrition without specific reference to sports or sustainability.

– Did not provide substantial evidence or were anecdotal in nature.

– Were published before 1999 unless deemed highly relevant for historical context.

Data were synthesized to identify common themes, gaps in the literature, and potential areas for future research. The synthesis aimed to draw connections between sustainable practices, the efficacy of functional foods in sports, and the broader implications for public health and environmental sustainability.

The review utilized a thematic analysis framework to categorize the literature into key themes, including:

– The role of functional foods in enhancing athletic performance.

– Environmental sustainability of various sports nutrition strategies.

– The intersection of nutrigenomics and sustainability in personalized nutrition.

– Public policy implications and recommendations for sustainable sports nutrition.

Each theme was analyzed in the context of its contribution to a sustainable food system, and the findings were integrated to propose a holistic approach to sustainable sports supplementation.

Functional foods and food sustainability

Definitions and principles of food sustainability and functional foods

Obtaining a reasonable definition of food sustainability is not easy. We could start with an authoritative definition of a sustainable diet. Recently, FAO proposed that a sustainable diet must (i) have low environmental impacts, (ii) contribute to food and nutrition security for a healthy life for present and future generations, (iii) be protective and respectful of biodiversity and ecosystems, (iv) be culturally acceptable, accessible, economically fair, and affordable, and (v) be oriented to optimize natural and human resources [12]. This definition, today, is to take as a description of a horizon to be asymptotically achieved, although some hopes must be turned to powerful information technology, e.g. food informatics. The prediction grows as does the global human population, which calculates that in 2050, there will be 10 billion humans, making it urgent to start producing, consuming, recycling, and disposing of in a sustainable way according to the concept of one health (COH), that is, for the health of every living being on the planet and of the planet itself. The innovative concepts of the Internet of Things (IoT), together with Artificial Intelligence (AI), surely is the best way to regulate all the productive processes and human life itself by utilizing computational resources and sensors that often and continuously supplement and manage objects/events every day [13]. With this revolutionary paradigm change, it will be possible to build smart farmers and smart industries (like those already described with the term "Industry 4.0") in which all the highly complex processes can be integrated and, at best, fitted by informatics and internet networks to produce the best food with optimal efficiency of processes at all levels and that is respectful of the COH. By hopefully working in this direction, we can assume that the definition previously enounced, in the near future, will be the best and usual description of food sustainability.

Considering the collective imagination associated today with the concept of "functional food", in light of what was reported above, it is necessary to diversify and better specify some indispensable additional characteristics that must be part of the definition of functional food or its productive processes. Granato et al. [14] by starting with a common definition of a functional food, proposed a guideline to attest that some ingredients or foods truly deserve this special designation. Are these concepts sufficient to gain a modern definition that is respectful of sustainability and the COH? It is surely necessary to apply innovative processing technologies and food-processing alternatives [15] that utilize less energy and can be eco-friendly [16]. However, it is not enough for current times, it is important to also add some ethical issues like accessibility to less wealthy people and use in all levels of legally conducted sports. Moreover, it could be desirable that they might be performed with optimal efficiency of the processes at all levels and respectful of the COH, something that can technically only be possible today through the application of IoT and AI principles, concepts, and supports.

Production of algae is one of the most advanced processes in terms of sustainability of manufacturing. Neo et al. [17] reported that this is performed using IoT and AI techniques utilizing high levels of a smart system, real-time monitoring, remote control system, quick response to sudden events, prediction, and characterization, as well as interconnectivity, archiving, analyzing, and automation.

Strategies to improve sustainability in the food sector

The master strategy to ameliorate crops seems to be ancient, as is natural nitrogen-assisted agriculture. The vast number of humans on Earth, makes these mechanisms insufficient, thus, it becomes necessary to use large amounts of nitrogen fertilizer [18] with problematic consequences in terms of NH3, N2O, and N2 in the atmosphere due to ammonium volatilization and nitrate denitrification [19]. The ecological transition, in the past years, has triggered considerable efforts to develop a highly efficient use of nitrogen by plants by dissecting the genetic basis underlying nitrogen use efficiency (NUE) [20]. Rice, with respect to other food plants, has a much greater understanding of its genetic makeup. For rice, Quantitative Trait Loci (QTLs) have already been identified, which determine underlying plant nitrogen management and helped develop the "Green Super Rice", a plant with excellent properties in terms of nitrogen use efficiency and strong resistance to biotic and abiotic stresses [21]. Since this last improvement follows the canons of the COH, we can name this process "sustainably" since it positively involves the root microbiota. It is desirable that the genetic improvement of every food-involved crop can be managed by these techniques [22] to gain a generalized upgrading of their sustainability. The scientists know that today, by GWAS, WES, and NGS-based genomic technologies, this goal can be realized, but while the science is ready, the global food policy still requires some improvement for allocating resources to applied research using the COH sustainability criteria.

Today, nanotechnology-based strategies can be useful to improve the sustainability of foods or their manufacturing processes, especially to enhance their bioavailability or to thwart some absences in fortification-derived foods, like vitamins and micronutrients with the addition of antioxidants, antimicrobials, as well as smart food packaging. These phytochemical-based nanocarriers promise to be environmentally sustainable, less harmful, and affordable [23]. Although a large quantity of literature describes their useful characteristics to improve nutraceuticals or foods, in our opinion, it still needs to be clarified that all the productive processes for industrial manufacturing of nanoparticles are sustainable and COH-respectful. More recently, Fisher [24] critically discussed the sustainability and green concepts of nanoparticles, leading to a re-thinking of some productive steps, particularly regarding the conventional solvents for which the dissolution of the polymer suffers.

The history of man has always proceeded towards indispensable progress, especially in the food sector, for the obvious reasons of self-sustainment. It must no longer happen that this must be contrasted with a regression of other living beings or the planet in general. We are witnessing the disastrous returns of wicked choices of this type. At least we scientists, by our very essence and rigour, plan for progress only if it is sustainable and respectful of COH, at least to the best of our current knowledge.

Benefits of functional foods for health and sportive needs

Functional foods, rich in bioactive compounds and essential nutrients, offer significant advantages for general health and athletic performance. These foods, which include items like fortified dairy products, whole grains, nuts, fish, and various fruits and vegetables, not only enhance overall well-being but also satisfy the specific nutritional requirements of athletes. For general health, functional foods contribute to the prevention of chronic diseases, support immune function, and improve gut health through their high content of vitamins, minerals, antioxidants, and fibre [25]. From a sports perspective, they aid in quicker recovery, improved energy metabolism, and enhanced endurance and strength [26].

Berries, for example, are a vibrant example of functional foods that deliver a multitude of health benefits. Packed with anthocyanins, a class of powerful antioxidants, berries offer anti-inflammatory and immune-boosting properties [27]. Anthocyanins can help reduce chronic inflammation, a low-grade simmering process linked to various health concerns [28]. Regular berry consumption may also contribute to a stronger immune system, potentially reducing the frequency and severity of common illnesses [29].

Beyond anthocyanins, berries are a rich source of essential vitamins and minerals. They are particularly abundant in vitamin C, a crucial nutrient for collagen production, immune function, and iron absorption. Many berries are also good sources of fibre, which promotes gut health, digestive regularity, and feelings of satiety [30].

The benefits of berries extend beyond general health, offering valuable advantages for athletes as well. The potent anti-inflammatory properties of anthocyanins can help reduce exercise-induced muscle soreness and inflammation, leading to faster recovery times between training sessions [31]. This translates to improved performance and a quicker return to peak training intensity.

Furthermore, some berries, like blueberries, are a good source of carbohydrates, particularly fructose. While often demonized, fructose can be a beneficial source of energy during moderate-intensity exercise [32]. Additionally, berries are a good source of nitrates, natural compounds that may improve blood flow and oxygen delivery to muscles, potentially enhancing exercise performance [33].

The inclusion of functional foods in an athlete's diet can enhance muscle protein synthesis and reduce exercise-induced oxidative stress. Lean protein sources, particularly fatty fish rich in omega-3 fatty acids, are prime examples of functional foods that can significantly benefit athletes seeking to improve endurance and strength. The role of dietary fatty acids is particularly crucial as they can positively influence serum lipid profiles, which is essential for cardiovascular health [34]. Indeed, omega-3s, particularly the types eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), play a crucial role in muscle function and metabolism [35]. Furthermore, studies suggest that omega-3 supplementation may enhance muscle protein synthesis, the process of building and repairing muscle tissue, which is crucial for muscle growth and adaptation to exercise [35].

It is well known that intense exercise can increase protein turnover even though this does not contribute much to ATP production except under conditions of low carbohydrate availability, where the contribution of amino acid metabolism is increased. After exercise, it is recommended to supplement with adequate protein intake, especially from high-quality sources like fatty fish, which helps with muscle protein synthesis this becomes even more critical for athletes engaged in intense training regimens where muscle breakdown can be more pronounced [36]. Additionally, omega-3s possess anti-inflammatory properties, which can help reduce muscle soreness and improve recovery after exercise [37].

Omega-3s in fatty fish can also improve insulin sensitivity, which allows muscles to take up glucose (blood sugar) more effectively. This translates to better energy utilization during exercise and potentially delays the onset of fatigue [38].

By incorporating functional foods into their diet, individuals can achieve a balanced nutritional profile that supports their daily health and athletic goals. This integration not only ensures the intake of essential nutrients but also leverages the specific health benefits these foods offer, making them a strategic component in both preventive health care and sports nutrition.

In addition to functional foods, given the high importance of protein consumption in sports nutrition, the use of integrated ecosystems, such as aquaponic ones, and the use of natural breeding techniques, such as regenerative grazing, could be a viable way to reduce the environmental impact [39, 40]. Microalgae and cyanobacteria, for instance, could be utilized to produce dietary supplements and food products with high protein and lipid content [41]. Other modern techniques, such as the extraction of meat proteins of plant origin could be employed to create foods that not only possess a comparable functional nutritional profile to conventionally commercialized products but are even enhanced [42]. Furthermore, all these strategies serve to reduce excessive land use and livestock exploitation as a sustainable way to meet human food intake needs, especially in sports nutrition.

Nutrigenomic properties of functional food

Foods with nutrigenomic properties and personalized nutrition

Molecules originating from our daily dietary intake constitute a significant environmental influence to which we are consciously exposed [43].

For this reason, the connection between food and gene expression, also known as nutrigenomics, is increasingly capturing attention. Nutrigenomics, integrating various branches of science including nutrition, bioinformatics, genomics, molecular biology, molecular medicine, and epidemiology, explores the daily visceral link between our diet and genome, revealing how nutrition influences human evolution and impacts susceptibility to diseases like diabetes and atherosclerosis [44, 45].

In this complex field, the trinomial of nutrigenetics, epigenomics, and the exposome must be given proper emphasis. As described by Ordovas et al. [46], nutrigenetics is a field of personalized nutrition that examines the different phenotypic responses, such as weight, blood pressure, plasma cholesterol, or glucose levels, to a specific diet, like a low-fat or Mediterranean diet, based on the individual's genotype. Epigenomics, a branch of genomics, investigates epigenetic changes, such as methylation, histone modification, and microRNA, that affect the expression and function of an organism's genetic material, without altering the nucleotide sequence of the DNA. Subsequently, the activity of the exposome comes into play, which encompasses the range of environmental factors, including stress, physical activity, and diet, to which an individual is continuously exposed [46]. These factors can modulate gene activity and thus influence human health.

International genome projects utilizing whole-genome sequencing analyses have offered a thorough depiction of genetic variations throughout the human genome, encompassing single nucleotide polymorphisms (SNPs), copy number variations (CNVs), and other structural variants [47]. Recent nutrigenomic studies have identified genetic variants associated with susceptibility to various diseases in response to dietary factors. These scientific advancements hold great promise for revolutionizing the treatment and prevention of chronic diseases by potentially predicting individual risks, elucidating disease aetiology, and enabling personalized nutritional management [45, 48–50].

The use of herbs and spices as seasonings in the Mediterranean diet can significantly enhance the nutraceutical value of a typical meal due to their high content of antioxidant phytochemicals [51].

La Scala et al. [52] offer an overview of bioactive molecules found in select plants commonly used in the Mediterranean diet. Their study explores the human nutrigenomic effects and health benefits, alongside the environmental advantages and sustainability derived from their cultivation. The caper plant (Capparis spinosa L., order Brassicales, family Capparaceae), widely distributed in the Mediterranean region, is notable for its high content of quercetin and kaempferol. According to La Scala et al. [52], it ranks among the top plant species in terms of these bioactive compounds by weight. This positions it as a promising candidate for future research and applications, particularly in managing type 2 diabetes mellitus (T2DM). Studies suggest that quercetin, in particular, interacts with DNA and exhibits protective effects against type 2 diabetes [53]. Overall, quercetin and kaempferol, found abundantly in the caper plant, demonstrate nutrigenomic effects by influencing gene expression through mechanisms like DNA methylation regulation, inhibition of histone acetylation, and promotion of genomic stability [52]. Although capers are not characterized by a high antioxidant potential, experimental results indicate that extracts of capers in small quantities, typically used as a culinary flavouring, are effective in preventing lipid peroxidation in red meat during digestion [54].

Another typical example of the Mediterranean diet is extra virgin olive oil (Olea Europaea L., EVOO), an essential food that has naturally diversified into numerous cultivars and is primarily cultivated today in Mediterranean countries such as Italy, Spain, and Greece [55, 56]. According to De Santis et al. [56], nutrigenomic studies have shown that regular consumption of extra virgin olive oil (VOO) with a high polyphenol content (HPC) can modulate pathways related to inflammation, oxidative stress, and lipid metabolism, compared to olive oil with a low polyphenol content (LPC) in healthy populations. Polyphenol-enriched extra virgin olive oil appears to directly influence the transcriptome and miRNome, promoting human health through its anti-inflammatory, anti-cancer, and antioxidant properties, as well as modulating glucose and lipid metabolism [56].

Despite the limited number of studies on gene-diet interactions in athletes, it is well-established that serum levels and the intake of various nutrients and bioactive compounds can influence health, body composition, and athletic performance [57]. Numerous studies have focused on caffeine, a compound found in plants such as coffee, tea, cocoa, and guarana, commonly used as an ergogenic aid in sports. Individual differences in response to caffeine, attributed to genetic variations in the CYP1A2 and ADORA2A genes, are still under investigation [58]. These findings suggest that, in the future, genetic testing could become a valuable tool for nutritionists and specialists in formulating personalized diets, thereby enhancing athletic performance and health [57].

The connection between nutrition, nutrigenomics, and athletic performance

Traditionally, sports nutrition focused on a one-size-fits-all approach. However, advancements in science are revealing the intricate link between an athlete's genes, their dietary choices, and ultimately, their performance. The interplay between nutrition, nutrigenomics, and athletic performance is a growing field that reveals how genetic makeup influences individual responses to dietary intake, thereby optimizing athletic performance. By delving into the intricate link between genes and nutrient responses, nutrigenomics holds immense potential for personalized nutrition plans. This personalized approach, informed by an athlete's unique genetic makeup, can unlock a new level of optimization and holds promise in tailoring dietary recommendations to optimize athletic performance and overall health. Functional foods or tailored diets designed based on individual needs can provide a sustainable edge, enhancing factors like energy production, recovery, and overall well-being.

Nutrition serves as the cornerstone for athletic success, providing essential macronutrients and micronutrients required for energy production, recovery, and overall health. Nutrigenomics takes this a step further by tailoring dietary recommendations based on an individual's genetic profile [57, 59]. This personalized approach can enhance performance outcomes by addressing specific nutritional needs and potential deficiencies. For instance, genetic variations can affect nutrient metabolism, influencing how an athlete's body utilizes carbohydrates, fats, and proteins [57]. By understanding these genetic predispositions, athletes can adjust their diets to improve endurance, strength, and recovery time [57, 60]. A recent study by Zulqarnain et al. [61] underscores the complex dynamics between gene-diet interactions and their implications for athletic performance, highlighting significant variability in recovery rates and performance among athletes [61]. Overall, the integration of nutrition and nutrigenomics provides a comprehensive framework for maximizing athletic performance through individualized dietary interventions. In fact, by understanding these gene-diet interactions, sports nutritionists can create personalized strategies that maximize energy production, recovery, and overall well-being, propelling athletes to achieve their peak potential.

Development of sustainable supplements for sportive

Nutritional needs of athletes

Nutrition plays a key role in the lives of athletes in sustaining and enhancing sports performance by significantly influencing their performance and general well-being [62]. To realize their full potential, athletes must follow a well-balanced diet, customized to their specific nutritional needs. This approach not only allows them to achieve optimal levels of performance but also facilitates efficient recovery and reduces the risk of injury [63]. In addition to maintaining a balanced diet, many athletes use supplements to support their training goals. These supplements can cover nutritional deficiencies, improve recovery, promote muscle synthesis, increase energy levels, and optimize performance in their respective sports disciplines [64]. Athletes must be able to obtain adequate macronutrients (protein, carbohydrates, and fat) and micronutrients through a variety of foods, considering food composition, timing of nutrient intake, use of supplements, and energy balance. Furthermore, the nutritional needs of athletes can vary greatly depending on the sport, location, time of the season, and training or rest days. Most athletes aim to increase lean muscle mass, lose fat, or maintain current body composition, without hindering performance on the field [65]. The main macronutrients (protein, carbohydrates, and fat) are consumed according to one's training goals, such as gaining muscle or losing fat while maintaining lean mass and improving performance. Carbohydrates are crucial for improving performance in endurance and high-intensity sports and can be metabolized aerobically and anaerobically, making them particularly crucial for athletic performance [65]. This is due to the increased availability of exogenous carbohydrates and the ability to store in the form of glycogen in the muscles and liver. During training, endogenous carbohydrate reserves are progressively depleted due to energy expenditures. Rapid carbohydrate replenishment after training is essential to restore and optimize glycogen reserves for subsequent training sessions [66]. The amount of carbohydrate required varies according to the type of physical activity; in general, for low-intensity physical activity 3–5 g/kg/body weight (bw), at moderate intensity 5–7 g/kg/bw, at high intensity 6–10 g/kg/bw, and 8–12 g/kg/bw for very intense activity [67]. The timing of carbohydrate intake indicates that before activity, it is important to include foods with a low to moderate glycemic index (GI) to maintain stable blood glucose levels. It is only indicated during endurance activities or intense training and is essential to maintain energy availability and prevent premature depletion of muscle glycogen. After exercise, it is essential to take carbohydrates within the first two hours post-workout as this can significantly improve muscle glycogen synthesis. An intake of 1.0–1.5 g of carbohydrate per kg/bw per hour immediately after exercise is recommended, and maintain this intake at 30-minute intervals for up to 6 hours after training. Postponing carbohydrate intake by 2 hours can reduce glycogen resynthesis rates by 45% [68]. Concerning protein, which is essential for preserving and optimizing muscle mass, improving performance, or accelerating recovery, recent studies indicate that alterations in physical activity and nutritional intake have a more pronounced effect on muscle protein synthesis than degradation [69, 70]. The quality of proteins is assessed according to their composition in essential amino acids and their digestibility. Animal proteins (whose main sources include meat, fish, eggs, milk and dairy products) tend to score higher than plant proteins in terms of biological value based on their content of essential and branched-chain amino acids (BCAAs). Plant proteins have a lower biological value, lacking some essential amino acids; however, by combining them with different plant sources, such as legumes, cereals, nuts and seeds, it is possible to obtain a complete amino acid profile [71]. The athletes' protein requirements also vary according to the type of sport, training intensity, and specific goals. For endurance sports, maintaining and building muscle mass, 1.4–2.0 g/kg/bw is suggested, but for strength sports and periods of caloric deficit, this limit can reach or exceed 3 g/kg/bw [72]. For instance, male competitive bodybuilders can get up to 4.3 g/kg/day, and females up to 2.2 g/kg/day overall during a pre-competition phase [73]. Regarding the timing of protein intake, it is recommended to take a protein meal about 3–4 hours before training, as this can help maintain muscle growth and improve muscle recovery. There is no particular scientific evidence to support the usefulness of protein intake during exercise, although there may be a positive synergistic effect on production levels and hormones with an anabolic effect (insulin, growth hormones, IGF-1) [74]. The consumption of high-quality protein within two hours of training is essential to stimulate muscle protein synthesis and reduce protein degradation. A common recommendation is to consume around 0.31 g/kg of rapidly digestible protein after training. In this regard, it may be useful to use protein supplements such as whey protein, which not only provides an easily digestible source and contains a high level of essential amino acids that improve muscle protein synthesis, aiding post-exercise recovery, but also represents a viable and simple alternative to protein foods [75]. Thus, ultimately, recommendations vary according to the type of physical activity and individual goals, with an emphasis on meeting protein requirements through a combination of food sources and supplements. Regarding the importance of fats for athletes, they are an essential component of the diet, playing a crucial role in providing energy, supporting cellular function, and facilitating the absorption of fat-soluble vitamins (A, D, E, and K). Fats are particularly important for prolonged endurance activities as they provide a concentrated and long-lasting source of energy [76]. Of particular importance, as already mentioned, are omega-3 fatty acids, which are crucial for reducing inflammation and supporting brain function, aiding muscle recovery, reducing post-workout pain, and improving cardiovascular health, which is essential for endurance athletes. Athletes should aim to get between 20–35% of their total calories from fat, limiting saturated fat intake to less than 10% of total daily calories. Recognizing the unique challenges faced by athletes, the importance of personalizing nutritional plans to meet individual requirements is emphasized [77]. Macronutrients, including carbohydrates, proteins, and fats, play a critical role in athletic nutrition. An adequate intake of carbohydrates is necessary to support energy during training and recovery. Proteins are essential for muscle synthesis and repair, while fats, particularly omega-3 fatty acids, are important for reducing inflammation and supporting general health.

Incorporating sustainability into supplement production

To incorporate sustainability into supplement production, one should prefer organic, plant-based sources. This would help the process for certifications of Fair Trade or the Rainforest Alliance and would ensure ethical and sustainable harvesting practices. One of the characteristics of sustainable sourcing is the presence of ingredients with minimal processing [78]. Macroalgae are a perfect source of ingredients for extracting sustainable raw materials. Algae cultivation requires minimal resources, mitigating environmental issues such as ocean acidification [79]. Macroalgae are on nutraceutical food lists because they are abundant in bioactive substances. They are rich in (1) polysaccharide-like, agar, fucoidan, alginate and carrageenan; (2) proteins like phycobiliproteins; (3) micronutrients like manganese, copper, zinc, and iron; (4) carotenoids like fucoxanthin and β-carotene phenolic. It has been noticed that algae have higher protein values than legumes and soy. Their protein content ranges from about ten to thirty percent of dry weight, making them valuable for various dietary lifestyles, including vegan and vegetarian diets [80]. Therefore, algae offers high protein content and minimal environmental impact. Their composition is of value for sportive supplementation [81]. They can be considered safe for food production because compounds such as polysaccharides extracted from algae are already used in the food industry as thickening and stabilizing agents to improve the quality of the final product and extend its shelf life. Incorporating sustainability into supplement production is also important in the packaging. In this view, the natural biopolymer pectin is a sustainable alternative to synthetic plastics. Pectin is extracted from the food waste biomass. Industrial plant wastes offer a wide range of possibilities for valorization, still being rich in high-value molecules such as secondary metabolites [82]. Pectin could be widely utilized for nutraceutical and food applications, considering its application not only as a sustainable biopolymer for food packaging and preservation but also as an encapsulating agent and a functional and emulsifying agent in low-calorie products [83]. At present, about 85 percent of commercial pectin is extracted from citrus peels, and about 14 percent is extracted from apple pomace, while just less than one percent is from sugar beet pulp [84]. Another emerging bioeconomy sector with the potential to incorporate sustainability into supplement production is the synthesis of oligosaccharides from renewable sources like lignocellulosic substrates. We have to consider that in contrast to the past when supplementation of first-generation functional foods was mainly dependent on minerals and vitamins, now the attention of researchers has shifted towards prebiotics and probiotics. This is because it is now well known that microbiota plays a crucial role in the modulation of physiological responses for human health. These non-digestible oligosaccharides, known as prebiotics, are beneficial for the gut microbiota residing in the digestive system [85]. Commonly known prebiotics are galactooligosaccharides (GOS), xylooligosaccharides (XOS), fructooligosaccharides (FOS), mannan oligosaccharides (MOS), and inulin. They are synthesized through enzymatic approaches or whole-cell mediated methods using natural or agricultural waste substrates [86]. GOS, FOS, MOS, and inulin are the most common prebiotics, thanks to their ability to boost the growth and viability of bacteria, and are often supplemented in functional beverages [87]. Interestingly, some prebiotics can also ameliorate the quality, texture, and sensory properties of food. In conclusion, by focusing on these areas, supplement companies could create products that are good for sport and the planet. This resonates with the growing trend of athletes seeking eco-friendly and ethically sourced supplements. It is essential to educate consumers about the environmental impact of traditional supplement production and the benefits of sustainable options. Also, it is necessary to explore emerging sustainable ingredients, including algae protein or insect-derived protein powders.

Using functional foods to formulate supplements

Functional foods provide a palatable and effective way to hydrate and replenish electrolytes. However, it would be better to deliver it through a regular diet by using food as a carrier for bioactive compounds [88] instead of using it as supplements, like tablets or capsules. However, certain bioactive components can be extracted and concentrated to create supplements. Examples of functional foods that can be used in supplement formulation are (1) Berries because they are rich in anthocyanins, which are antioxidants that may help reduce inflammation and improve cognitive function; (2) Cruciferous vegetables like broccoli and cauliflower, because they contain sulforaphane, a compound with potential benefits for cancer prevention and detoxification; (3) Fatty fish including salmon and sardines because they are rich in omega-3 fatty acids, which are important for heart and brain health; (4) Garlic because it contains allicin, a compound with potential benefits for immune function and heart health; (5) Green tea that is rich in catechins, antioxidants that may help boost metabolism and improve cognitive function; and (6) Soybeans that contains isoflavones, plant-based estrogens with potential benefits for bone health and reducing menopausal symptoms [89].

These ingredients can be used to formulate functional sports drinks that play an important role in hydrating, improving athletic performance, and preventing or helping specific health conditions. Their formulas can be designed specifically to increase energy, improve mental focus, and/or prevent bone and joint pain. In the sports context, the principal function of such drinks is to hydrate athletes and restore electrolytes and carbohydrates [90]. In general, simple carbohydrates are used for a quick burst of energy, while complex carbohydrates provide sustained energy. These sports drinks are developed to provide essential salts like potassium, sodium chloride, calcium, phosphate, and magnesium, which can be lost by sweating during training and competition [91]. Other functional drinks may contain amino acids, which are used to slow fatigue and improve muscle function [92]. More drinks may contain B vitamins, which are used to boost metabolism and generate energy. While functional foods themselves can't be used whole in supplements, the beneficial bioactive compounds can be extracted and concentrated to create targeted supplements [93]. Thus, if the goal is to improve health, it's generally recommended to focus on incorporating a variety of functional foods into your diet first. This will ensure you're getting a broad range of nutrients and health-promoting combinations. Supplements can be a helpful tool to fill any nutrient gaps, but they shouldn't replace a healthy diet.

Advantages of sustainable food over traditional supplements

Sustainable food offers several advantages over traditional supplements. First of all, the health benefits because in food there is a wider range of nutrients. It contains various vitamins, minerals, antioxidants, and other beneficial compounds that work synergistically to promote one's health [94]. Supplements often focus on isolated nutrients. Thus, supplements lack the synergistic effects of nutrients and may not be as effective. We recently showed that the production of lettuce with saline increased the content of polyphenols and ameliorated hepatic, lipid, and bone homeostasis in healthy adults [95]. It may positively impact other physiological systems [96–98]. This kind of approach has several advantages like the reduction in exposure to chemicals. In fact, we are conscious that sustainable practices point out to minimize the use of pesticides and antibiotics, leading to potentially higher nutrient content, and reducing the health risks of the food itself. As we stated, it also promotes fresh and local (kilometer zero) production by growing, raising, processing, and consuming food within a short distance. This also means fresher foods with potentially higher levels of vitamins and possibly a better taste. There are environmental benefits. There is a reduction in the environmental impact. Sustainable practices like organic farming work to reduce soil erosion, conserve water, and promote biodiversity [4]. Supplements have more greenhouse gas emissions than seasonal produce because they are produced and shipped long distances. In our opinion, with climate change occurring and the reduction of rain in some counties and, consequently, water, the consumption of sustainable food can benefit the small local economy by supporting agriculture that is committed to environmentally friendly practices. Supplements are valuable and necessary for people with specific deficiencies or dietary restrictions. In the specific case of sports supplements, we are conscious that they are among the fastest-growing products on the market over the last few decades. Their consumption is no longer restricted to athletes only, in line with increased attention on a healthy lifestyle [99]. In response, researchers and food innovators must explore diverse avenues to meet their needs while mitigating the environmental impact of food production. For example, seaweed proteins clearly represent a promising and sustainable solution for meeting global protein demands while addressing environmental, health, and societal challenges. As evidenced by their nutritional richness, functional versatility, and eco-friendly cultivation, seaweed proteins offer a viable alternative to conventional protein sources [78]. Thus, similar to seaweed, we need an effort towards sustainable food with minimal resource requirements and the ability to thrive in diverse environments to play a pivotal role in the sustainable food systems of the future.

Conclusions

The union of sustainable practices, functional foods, and nutrigenomics in sports could represent a promising road for enhancing athlete well-being and minimizing environmental impact (Figure 1). However, several challenges and potential obstacles lie ahead. The potential paths to follow, in our opinion, are personalized nutrition, sustainable ingredient sourcing from local and organic farming, functional food development by using alternative protein sources, and waste reduction. The potential obstacles and, therefore, limitations are the regulatory hurdles, the consumer acceptance (due to cost, taste, and convenience), the limited research in the field up to date, the certification and the traceability of the products. Government policies must make additional efforts, as they shape farmers' production strategies, influencing both resource management and environmental sustainability. For instance, the introduction of subsidies and regulations aimed at promoting sustainable practices could increasingly encourage farmers to adopt eco-friendly methods, reducing reliance on harmful chemicals like pesticides and chemical fertilizers, and reducing environmental degradation. This would speed up the process of sustainability for our countries.

Ethical approval

The conducted research is not related to either human or animal use.

Conflict of interest

The authors state no conflict of interest.

Disclosure statement

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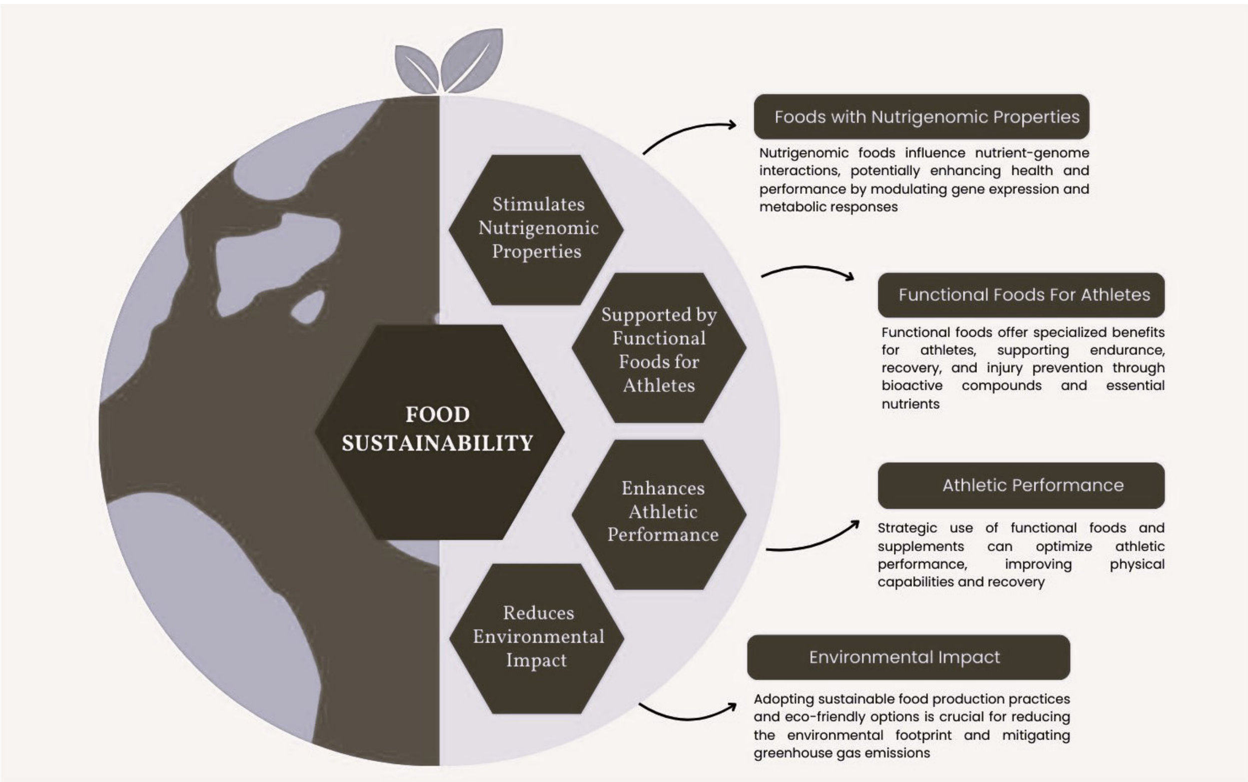

Figure 1. Benefits of food sustainability application for athletes and the planet

References

[1] Mouat AR. Sustainability in food-waste reduction biotechnology: a critical review. Curr Opin Biotechnol. 2022;77:102781; doi: 10.1016/j.copbio.2022.102781.

[2] Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello FN, Leip A. Food systems are responsible for a third of global anthropogenic GHG emissions. Nat Food. 2021;2:198–209; doi: 10.1038/s43016-021-00225-9.

[3] Gardner G, Burton W, Sinclair M, Bryant M. Interventions to strengthen environmental sustainability of school food systems: narrative scoping review. Int J Environ Res Public Health. 2023;20(11):5916; doi: 10.3390/ijerph20115916.

[4] Conrad Z, Niles MT, Neher DA, Roy ED, Tichenor NE. Relationship between food waste, diet quality, and environmental sustainability. PLOS ONE. 2018;13:e0195405; doi: 10.1371/journal.pone.0195405.

[5] Serra-Majem L, Tomaino L, Dernini S, Berry EM, Lairon D, de la Cruz JN, Bach-Faig A, Donini LM, Medina F-X, Belahsen R, Piscopo S, Capone R, Aranceta-Bartrina J, La Vecchia C, Trichopoulou A. Updating the Mediterranean diet pyramid towards sustainability: focus on environmental concerns. Int J Environ Res Public Health. 2020;17(23):8758; doi: 10.3390/ijerph17238758.

[6] Macieira A, Barbosa J, Teixeira P. Food safety in local farming of fruits and vegetables. Int J Environ Res Public Health. 2021;18(18):9733; doi: 10.3390/ijerph18189733.

[7] Friel S, Baker PI. Equity, food security and health equity in the Asia Pacific region. Asia Pac J Clin Nutr. 2009;18(4):620–32.

[8] Gantenbein KV, Kanaka-Gantenbein C. Mediterranean diet as an antioxidant: the impact on metabolic health and overall well-being. Nutrients. 2021;13(6):1951; doi: 10.3390/nu13061951.

[9] Celebi Sozener Z, Ozdel Ozturk B, Cerci P, Turk M, Akin BG, Akdis M, Altiner S, Ozbey U, Ogulur I, Mitamura Y, Yilmaz I, Nadeau K, Ozdemir C, Mungan D, Akdis CA. Epithelial barrier hypothesis: Effect of the external exposome on the microbiome and epithelial barriers in allergic disease. Allergy. 2022;77:1418–49; doi: 10.1111/all.15240.

[10] Chen C, Chaudhary A, Mathys A. Dietary change scenarios and implications for environmental, nutrition, human health and economic dimensions of food sustainability. Nutrients. 2019;11(4):856; doi: 10.3390/nu11040856.

[11] Pröbstl-Haider U, Mostegl NM, Kelemen-Finan J, Haider W, Formayer H, Kantelhardt J, Moser T, Kapfer M, Trenholm R. Farmers' preferences for future agricultural land use under the consideration of climate change. Environ Manage. 2016;58:446–64; doi: 10.1007/s00267-016-0720-4.

[12] Karavasiloglou N, Pannen ST, Jochem C, Kuhn T. Sustainable diets and cancer: a systematic review. Curr Nutr Rep. 2022;11:742–52; doi: 10.1007/s13668-022-00442-z.

[13] Krupitzer C, Stein A. Food informatics – review of the current state-of-the-art, revised definition, and classification into the research landscape. Foods. 2021;10(11):2889; doi: 10.3390/foods10112889.

[14] Granato D, Barba FJ, Bursać Kovačević D, Lorenzo JM, Cruz AG, Putnik P. Functional foods: product development, technological trends, efficacy testing, and safety. Annu Rev Food Sci Technol. 2020;11:93–118; doi: 10.1146/annurev-food-032519-051708.

[15] Bursać Kovačević D, Maras M, Barba FJ, Granato D, Roohinejad S, Mallikarjunan K, Montesano D, Lorenzo JM, Putnik P. Innovative technologies for the recovery of phytochemicals from Stevia rebaudiana Bertoni leaves: a review. Food Chem. 2018;268:513–21; doi: 10.1016/j.foodchem.2018.06.091.

[16] Putnik P, Bursać Kovačević D, Režek Jambrak A, Barba FJ, Cravotto G, Binello A, Lorenzo JM, Shpigelman A. Innovative "green" and novel strategies for the extraction of bioactive added value compounds from citrus wastes – a review. Molecules. 2017;22(5):680; doi: 10.3390/molecules22050680.

[17] Neo YT, Chia WY, Lim SS, Ngan CL, Kurniawan TA, Chew KW. Smart systems in producing algae-based protein to improve functional food ingredients industries. Food Res Int. 2023;165:112480; doi: 10.1016/j.foodres.2023.112480

[18] Khush GS. Green revolution: the way forward. Nat Rev Genet. 2001;2(10):815–22; doi: 10.1038/35093585.

[19] Canfield DE, Glazer AN, Falkowski PG. The evolution and future of earth's nitrogen cycle. Science. 2010;330(6001):192–6; doi: 10.1126/science.1186120.

[20] Gao Y, Qi S, Wang Y. Nitrate signaling and use efficiency in crops. Plant Commun. 2022;3(5):100353; doi: 10.1016/j.xplc.2022.100353.

[21] Yu S, Ali J, Zhou S, Ren G, Xie H, Xu J, Yu X, Zhou F, Peng S, Ma L, Yuan D, Li Z, Chen D, Zheng R, Zhao Z, Chu C, You A, Wei Y, Zhu S, Gu Q, He G, Li S, Liu G, Liu C, Zhang C, Xiao J,

Luo L, Li Z, Zhang Q. From green super rice to green agriculture: reaping the promise of functional genomics research. Mol Plant. 2022;15(1):9–26; doi: 10.1016/j.molp.2021.12.001.
[22] Hu B, Wang W, Chen J, Yongqiang L, Chengcai C. Genetic improvement toward nitrogen-use efficiency in rice: lessons and perspectives. Mol Plant. 2023;16(1):64–74; doi: 10.1016/j.molp.2022.11.007.
[23] Singh AR, Desu PK, Nakkala RK, Vanitha K, Sushma D, Mohammad SA, Hinna H, Rajani BA, Prashant K. Nanotechnology-based approaches applied to nutraceuticals. Drug Deliv Transl Res. 2022;12:485–99; doi: 10.1007/s13346-021-009 60-3
[24] Fischer D. Sustainability in drug and nanoparticle processing. Handb Exp Pharmacol. 2024:284:45–68; doi: 10.1007/164_2023_659.
[25] Roberfroid MB. Concepts and strategy of functional food science: the European perspective. Am J Clin Nutr. 2000;71(6 Suppl):1660–4; doi: 10.1093/ajcn/71.6.1660S.
[26] Jeukendrup AE. Periodized nutrition for athletes. Sports Med. 2017;47(Suppl 1):51–63; doi: 10.1007/s40279-017-0694-2.
[27] Seeram NP. Berry fruits: compositional elements, biochemical activities, and the impact of their intake on human health, performance, and disease. J Agric Food Chem. 2008;56(3):627–9; doi: 10.10 21/jf071988k.
[28] Basu A, Rhone M, Lyons TJ. Berries: emerging impact on cardiovascular health. Nutr Rev. 2010; 68(3):168–77; doi: 10.1111/j.1753-4887.2010.00 273.x.
[29] Vahapoglu B, Erskine E, Subasi BG, Capanoglu E. Recent studies on berry bioactives and their health-promoting roles. Molecules. 2021;27(1):108; doi: 10.3390/molecules27010108.
[30] Bowen-Forbes CS, Zhang Y, Nair MG. Anthocyanin content, antioxidant, anti-inflammatory and anti-cancer properties of blackberry and raspberry fruits. J Food Comp Analysis. 2010;23(6): 554–60; doi: 10.1016/j.jfca.2009.08.012.
[31] Souza TCM, Goston JL, Martins-Costa HC, Minighin EC, Anastácio LR. Can anthocyanins reduce delayed onset muscle soreness or are we barking up the wrong tree? Prev Nutr Food Sci. 2022;27(3):265–75; doi: 10.3746/pnf.2022.27.3. 265.
[32] Fuchs CJ, Gonzalez JT, van Loon LJC. Fructose co-ingestion to increase carbohydrate availability in athletes. J Physiol. 2019;597(14):3549–60; doi: 10.1113/JP277116.
[33] Clements W, Lee S-R, Bloomer R. Nitrate ingestion: a review of the health and physical performance effects. Nutrients. 2014;6(11):5224–64; doi: 10.3390/nu6115224.
[34] Mensink RP, Zock PL, Kester AD, Katan MB. Effects of dietary fatty acids and carbohydrates on the ratio of serum total to HDL cholesterol and on serum lipids and apolipoproteins: a meta-analysis of 60 controlled trials. Am J Clin Nutr. 2003;77(5): 1146–55; doi: 10.1093/ajcn/77.5.1146.
[35] Jannas-Vela S, Espinosa A, Candia AA, Flores--Opazo M, Peñailillo L, Valenzuela R. The role of omega-3 polyunsaturated fatty acids and their lipid mediators on skeletal muscle regeneration: a narrative review. Nutrients. 2023;15(4):871; doi: 10.3390/nu15040871.
[36] Hargreaves M, Spriet LL. Skeletal muscle energy metabolism during exercise. Nat Metab. 2020;2: 817–28; doi: 10.1038/s42255-020-0251-4.
[37] Jouris KB, McDaniel JL, Weiss EP. The effect of omega-3 fatty acid supplementation on the inflammatory response to eccentric strength exercise. J Sports Sci Med. 2011;10(3):432–8.
[38] Chacińska M, Zabielski P, Książek M, Szałaj P, Jarząbek K, Kojta I, Chabowski A, Błachnio-Zabielska AU. The impact of OMEGA-3 fatty acids supplementation on insulin resistance and content of adipocytokines and biologically active lipids in adipose tissue of high-fat diet fed rats. Nutrients. 2019;11(4):835; doi: 10.3390/nu11040835.
[39] Bartelme RP, Smith MC, Sepulveda-Villet OJ, Newton RJ. Component microenvironments and system biogeography structure microorganism distributions in recirculating aquaculture and aquaponic systems. mSphere. 2019;4(4): e00143-19; doi: 10.1128/mSphere.00143-19.
[40] Gosnell H, Charnley S, Stanley P. Climate change mitigation as a co-benefit of regenerative ranching: insights from Australia and the United States. Interface Focus. 2020;10:20200027; doi: 10.1098/rsfs.2020.0027.
[41] Nicoletti M. Microalgae nutraceuticals. Foods. 2016;5(3):54; doi: 10.3390/foods5030054.
[42] Yu J, Wang L, Zhang Z. Plant-based meat proteins: processing, nutrition composition, and future prospects. Foods. 2023;12(22):4180; doi: 10.3390/foods12224180.
[43] Carlberg C, Raczyk M, Zawrotna N. Vitamin D: a master example of nutrigenomics. Redox Biol. 2023;62:102695; doi: 10.1016/j.redox.2023.102695.
[44] Carsten C, Ulven SM, Molnár F. Nutrigenomics. How Science Works. Cham: Springer; 2020.

[45] Kiani AK, Bonetti G, Donato K, Kaftalli J, Herbst KL, Stuppia L, Fioretti F, Nodari S, Perrone M, Chiurazzi P, Bellinato F, Gisondi P, Bertelli M. Polymorphisms, diet and nutrigenomics. J Prev Med Hyg. 2022;63(2, Suppl 3):125–41; doi: 10.15167/2421-4248/jpmh2022.63.2S3.2754.
[46] Ordovas JM, Ferguson LR, Tai ES, Mathers JC. Personalised nutrition and health. BMJ. 2018;361: bmj.k2173; doi: 10.1136/bmj.k2173.
[47] The 1000 Genomes Project Consortium; Auton A, Brooks LD, Durbin RM, Garrison EP, Kang HM, Korbel JO, Marchini JL, McCarthy S, McVean GA, Abecasis GR. A global reference for human genetic variation. Nature. 2015;526:68–74; doi: 10.1038/nature15393.
[48] Ramos-Lopez O, Milagro FI, Allayee H, Chmurzynska A, Choi MS, Curi R, De Caterina R, Ferguson LR, Goni L, Kang JX, Kohlmeier M, Marti A, Moreno LA, Pérusse L, Prasad C, Qi L, Reifen R, Riezu-Boj JI, San-Cristobal R, Santos JL, Martínez JA. Guide for current nutrigenetic, nutrigenomic, and nutriepigenetic approaches for precision nutrition involving the prevention and management of chronic diseases associated with obesity. J Nutrigenet Nutrigenomics. 2017;10(1–2):43–62; doi: 10.1159/000477729.
[49] Martínez JA. Perspectives on personalized nutrition for obesity. J Nutrigenet Nutrigenomics. 2014;7:I–III; doi: 10.1159/000365158.
[50] Meisel SF, Carere DA, Wardle J, Kalia SS, Moreno TA, Mountain JL, Roberts JS, Green RC; PGen Study Group. Explaining, not just predicting, drives interest in personal genomics. Genome Med. 2015;7:74; doi: 10.1186/s13073-015-0188-5.
[51] Caradonna F, Consiglio O, Luparello C, Gentile C. Science and healthy meals in the world: nutritional epigenomics and nutrigenetics of the mediterranean diet. Nutrients. 2020;12(6):1748; doi: 10.3390/nu12061748.
[52] La Scala S, Naselli F, Quatrini P, Gallo G, Caradonna F. Drought-adapted mediterranean diet plants: a source of bioactive molecules able to give nutrigenomic. Effects per sè or to obtain functional foods. Int J Mol Sci. 2024;25(4):2235; doi: 10.3390/ijms25042235.
[53] Felisbino K, Granzotti JG, Bello-Santos L, Guiloski IC. Nutrigenomics in regulating the expression of genes related to type 2 diabetes mellitus. Front Physiol. 2021;12; doi: 10.3389/fphys.2021.699220.
[54] Tesoriere L, Butera D, Gentile C, Livrea MA. Bioactive components of caper (Capparis spinosa L.) from sicily and antioxidant effects in a red meat simulated gastric digestion. J Agric Food Chem. 2007;55(21):8465–71; doi: 10.1021/jf0714113.
[55] Kalogiouri NP, Aalizadeh R, Thomaidis NS. Application of an advanced and wide scope non-target screening workflow with LC-ESI-QTOF-MS and chemometrics for the classification of the Greek olive oil varieties. Food Chem. 2018;256:53–61; doi: 10.1016/j.foodchem.2018.02.101.
[56] De Santis S, Cariello M, Piccinin E, Sabbà C, Moschetta A. Extra virgin olive oil: lesson from nutrigenomics. Nutrients. 2019;11(9):2085; doi: 10.3390/nu11092085.
[57] Guest NS, Horne J, Vanderhout SM, El-Sohemy A. Sport nutrigenomics: personalized nutrition for athletic performance. Front Nutr. 2019;6:8; doi: 10.3389/fnut.2019.00008.
[58] Yang A, Palmer AA, de Wit H. Genetics of caffeine consumption and responses to caffeine. Psychopharmacology. 2010;211:245–57; doi: 10.1007/s00213-010-1900-1.
[59] Volpes S, Cruciata I, Ceraulo F, Schimmenti C, Naselli F, Pinna C, Mauro M, Picone P, Dallavalle S, Nuzzo D, Pinto A, Caradonna F. Nutritional epigenomic and DNA-damage modulation effect of natural stilbenoids. Sci Rep. 2023;13:658; doi: 10.1038/s41598-022-27260-1.
[60] Semenova EA, Hall ECR, Ahmetov II. Genes and athletic performance: the 2023 update. Genes. 2023;14(6):1235; doi: 10.3390/genes14061235.
[61] Zulqarnain, Suleman S, Niaz AQ, Akram MN, Hadi B, Usman M, Sajjad M, Waseem M, Rajjab A, Muqarrab RM. The role of nutrigenomics in sports performance: a quantitative overview of gene-diet interactions. J Health Rehabil Res. 2024;4(1): 1713–8; doi: 10.61919/jhrr.v4i1.664.
[62] Thomas DT, Erdman KA, Burke LB. American College of Sports Medicine Joint Position Statement. Nutrition and athletic performance. Med Sci Sports Exerc. 2016;48(3):543–68; doi: 10.1249/MSS.0000000000000852. Erratum: Nutrition and athletic performance. Med Sci Sports Exerc. 2017;49(1):222; doi: 10.1249/MSS.0000000000001162.
[63] Papadopoulou SK. Rehabilitation nutrition for injury recovery of athletes: the role of macronutrient intake. Nutrients. 2020;12(8):2449; doi: 10.3390/nu12082449.
[64] Amawi A, AlKasasbeh W, Jaradat M, Almasri A, Alobaidi S, Hammad AA, Bishtawi T, Fataftah B, Turk N, Al Saoud H, Jarrar A, Ghazzawi H. Athletes' nutritional demands: a narrative review of nutritional requirements. Front Nutr. 2024;10; doi: 10.3389/fnut.2023.1331854.

[65] Henselmans M, Bjørnsen T, Hedderman R, Vårvik FT. The Effect of carbohydrate intake on strength and resistance training performance: a systematic review. Nutrients. 2022;14(4):856; doi: 10.3390/nu14040856.
[66] Podlogar T, Wallis GA. New horizons in carbohydrate research and application for endurance athletes. Sports Med. 2022;52(Suppl 1):5–23; doi: 10.1007/s40279-022-01757-1.
[67] Burke LM, Ackerman KE, Heikura IA, Hackney AC, Stellingwerff T. Mapping the complexities of Relative Energy Deficiency in Sport (REDs): development of a physiological model by a subgroup of the International Olympic Committee (IOC) Consensus on REDs. Br J Sports Med. 2023;57:1098–110; doi: 10.1136/bjsports-2023-107335.
[68] Li S, Kempe M, Brink M, Lemmink K. Effectiveness of recovery strategies after training and competition in endurance athletes: an umbrella review. Sports Med Open. 2024;10:55; doi: 10.1186/s40798-024-00724-6.
[69] Wirth J, Hillesheim E, Brennan L. The role of protein intake and its timing on body composition and muscle function in healthy adults: a systematic review and meta-analysis of randomized controlled trials. J Nutr. 2020;150(6):1443–60; doi: 10.1093/jn/nxaa049.
[70] Baranauskas M, Kupčiūnaitė I, Stukas R. Dietary intake of protein and essential amino acids for sustainable muscle development in elite male athletes. Nutrients. 2023;15(18):4003; doi: 10.3390/nu15184003.
[71] Goldman DM, Warbeck CB, Karlsen MC. Protein requirements for maximal muscle mass and athletic performance are achieved with completely plant-based diets scaled to meet energy needs: a modeling study in professional American football players. Nutrients. 2024;16(12):1903; doi: 10.3390/nu16121903.
[72] Oikawa SY, Brisbois TD, van Loon LJC, Rollo I. Eat like an athlete: insights of sports nutrition science to support active aging in healthy older adults. Geroscience. 2021;43:2485–95; doi: 10.1007/s11357-021-00419-w.
[73] Spendlove J, Mitchell L, Gifford J, Hackett D, Slater G, Cobley S, O'Connor H. Dietary intake of competitive bodybuilders. Sports Med. 2015;45:1041–63; doi: 10.1007/s40279-015-0329-4.
[74] Tezze C, Sandri M, Tessari P. Anabolic resistance in the pathogenesis of sarcopenia in the elderly: role of nutrition and exercise in young and old people. Nutrients. 2023;15(18):4073; doi: 10.3390/nu15184073.
[75] Ferrando AA, Wolfe RR, Hirsch KR, Church DD, Kviatkovsky SA, Roberts MD, Stout JR, Gonzalez DE, Sowinski RJ, Kreider RB, Kerksick CM, Burd NA, Pasiakos SM, Ormsbee MJ, Arent SM, Arciero PJ, Campbell BI, VanDusseldorp TA, Jager R, Willoughby DS, Kalman DS, Antonio J. International Society of Sports Nutrition Position Stand: effects of essential amino acid supplementation on exercise and performance. J Int Soc Sports Nutr. 2023;20(1):2263409; doi: 10.1080/15502783.2023.2263409.
[76] Fernández-Lázaro D, Arribalzaga S, Gutiérrez-Abejón E, Azarbayjani MA, Mielgo-Ayuso J, Roche E. Omega-3 fatty acid supplementation on post-exercise inflammation, muscle damage, oxidative response, and sports performance in physically healthy adults – a systematic review of randomized controlled trials. Nutrients. 2024;16(13):2044; doi: 10.3390/nu16132044.
[77] Baranauskas M, Kupčiūnaitė I, Lieponienė J, Stukas R. Association between variation in body fat mass magnitude and intake of nutrients, including carbohydrates, fat, and B vitamins, in a cohort of highly trained female athletes. Foods. 2023;12(22):4152; doi: 10.3390/foods12224152.
[78] Pereira L, Cotas J, Gonçalves A. Seaweed proteins: a step towards sustainability?. Nutrients. 2024;16(8):1123; doi: 10.3390/nu16081123.
[79] Tavares JO, Cotas J, Valado A, Pereira L. Algae food products as a healthcare solution. Mar Drugs. 2023;21(11):578; doi: 10.3390/md21110578.
[80] Chiocchio I, Mandrone M, Tomasi P, Marincich L, Poli F. Plant secondary metabolites: an opportunity for circular economy. Molecules. 2021;26(2):495; doi: 10.3390/molecules26020495.
[81] Adarshan S, Sree VSS, Muthuramalingam P, Nambiar KS, Sevanan M, Satish L, Venkidasamy B, Jeelani PG, Shin H. Understanding macroalgae: a comprehensive exploration of nutraceutical, pharmaceutical, and omics dimensions. Plants. 2023;13(1):113; doi: 10.3390/plants13010113.
[82] Dambuza A, Rungqu P, Oyedeji AO, Miya G, Oriola AO, Hosu YS, Oyedeji OO. Therapeutic potential of pectin and its derivatives in chronic diseases. Molecules. 2024;29(4):896; doi: 10.3390/molecules29040896.
[83] Singh NK, Baranwal J, Pati S, Barse B, Khan RH, Kumar A. Application of plant products in the synthesis and functionalisation of biopolymers. Int J Biol Macromol. 2023;237:124174; doi: 10.1016/j.ijbiomac.2023.124174.
[84] Frosi I, Balduzzi A, Moretto G, Colombo R, Papetti A. Towards valorization of food-waste-deri-

ved pectin: recent advances on their characterization and application. Molecules. 2023;28(17): 6390; doi: 10.3390/molecules28176390.

[85] Chavan AR, Singh AK, Gupta RK, Nakhate SP, Poddar BJ, Gujar VV, Purohit HJ, Khardenavis AA. Recent trends in the biotechnology of functional non-digestible oligosaccharides with prebiotic potential. Biotechnol Genet Eng Rev. 2023;39(2): 465–510; doi: 10.1080/02648725.2022.2152627.

[86] Narisetty V, Parhi P, Mohan B, Hazeena SH, Kumar AN, Gullón B, Srivastava A, Nair LM, Alphy MP, Sindhu R, Kumar V, Castro E, Awasthi MK, Binod P. Valorization of renewable resources to functional oligosaccharides: recent trends and future prospective. Bioresour Technol. 2022;346: 126590; doi: 10.1016/j.biortech.2021.126590.

[87] Mohanty D, Misra S, Mohapatra S, Sahu PS. Prebiotics and synbiotics: recent concepts in nutrition. Food Biosci. 2018;26:152–60; doi: 10.1016/j.fbio.2018.10.008.

[88] Anvarifard P, Ostadrahimi A, Ardalan M, Anbari M, Ghoreishi Z. The effects of propolis on pro--oxidant–antioxidant balance, glycemic control, and quality of life in chronic kidney disease: a randomized, double-blind, placebo-controlled trial. Sci Rep. 2023;13:9884; doi: 10.1038/s41598-023-37033-z.

[89] Boggia R, Zunin P, Turrini F. Functional foods and food supplements. Appl Sci. 2020;10(23):8538; doi: 10.3390/app10238538.

[90] Orrù S, Imperlini E, Nigro E, Alfieri A, Cevenini A, Polito R, Daniele A, Buono P, Mancini A. Role of functional beverages on sport performance and recovery. Nutrients. 2018;10(10):1470; doi: 10.3390/nu10101470.

[91] Aoi W, Naito Y, Yoshikawa T. Exercise and functional foods. Nutr J. 2006;5:15; doi: 10.1186/1475-2891-5-15.

[92] Saris WHM. Functional foods for athletes. Curr Opin Clin Nutr Metab Care. 1999;2(6):511–3; doi: 10.1097/00075197-199911000-00014.

[93] Siró I, Kápolna E, Kápolna B, Lugasi A. Functional food. Product development, marketing and consumer acceptance a review. appetite. 2008;51(3): 456–67; doi: 10.1016/j.appet.2008.05.060.

[94] Barrett CB, Benton T, Fanzo J, Herrero M, Nelson RJ, Bageant E, Buckler E, Cooper K, Culotta I, Fan S, Gandhi R, James S, Kahn M, Lawson-Lartego L, Liu J, Marshall Q, Mason-D'Croz D, Mathys A, Mathys C, Mazariegos-Anastassiou V, Miller A, Misra K, Mude A, Shen J, Sibanda LM, Song C, Steiner R, Thornton P, Wood S. Socio--Technical Innovation Bundles for Agri-Food Systems Transformation. Cham: Springer International Publishing; 2022.

[95] Ferrantelli V, Vasto S, Alongi A, Sabatino L, Baldassano D, Caldarella R, Gagliano R, Di Rosa L, Consentino BB, Vultaggio L, Baldassano S. Boosting plant food polyphenol concentration by saline eustress as supplement strategies for the prevention of metabolic syndrome: an example of randomized interventional trial in the adult population. Front Nutr. 2023;10:10:1288064; doi: 10.3389/fnut.2023.1288064.

[96] Mule F, Amato A, Baldassano S, Serio R. Evidence for a modulatory role of cannabinoids on the excitatory NANC neurotransmission in mouse colon. Pharmacol Res. 2007;56(2):132–9; doi: 10.1016/j.phrs.2007.04.019.

[97] Baldassano S, Amato A, Rappa F, Cappello F, Mulè F1. Influence of endogenous glucagon-like peptide-2 on lipid disorders in mice fed a high-fat diet. Endocr Res. 2016;41(4):317–24; doi: 10.3109/07435800.2016.1141950.

[98] Baldassano S, Tesoriere L, Rotondo A, Serio R, Livrea MA, Mulè F. Inhibition of the mechanical activity of mouse ileum by cactus pear (Opuntia ficus indica, L, Mill.) fruit extract and its pigment indicaxanthin. J Agric Food Chem. 2010;58(13): 7565–71; doi: 10.1021/jf100434e.

[99] Maughan RJ, Burke LM, Dvorak J, Larson--Meyer DE, Peeling P, Phillips SM, Rawson ES, Walsh NP, Garthe I, Geyer H, Meeusen R, van Loon LJC, Shirreffs SM, Spriet LL, Stuart M, Vernec A, Currell K, Ali VM, Budgett RG, Ljungqvist A, Mountjoy M, Pitsiladis YP, Soligard T, Erdener U, Engebretsen L. IOC consensus statement: dietary supplements and the high-performance athlete. Br J Sports Med. 2018;52(7):439–55; doi: 10.1136/bjsports-2018-099027.