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Update on vegetarian and vegan athletes: a review

Kenneth Vitale[1*] and Shawn Hueglin[2]

[1] *Department of Orthopedic Surgery, Division of Sports Medicine, University of California San Diego, 9300 Campus Point Drive, #7894, La Jolla, CA 92037, USA*
[2] *Senior Sports Dietitian, United States Olympic Committee, 2800 Olympic Parkway, Chula Vista, CA 91915, USA*

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Abstract Interest in vegetarian and vegan diets continues to grow, not only in the general population, but in the high-performing athlete. Vegetarian diets may lower risk of chronic diseases and have proposed ergogenic benefits to the athlete regarding exercise performance and enhanced recovery. However, controversy and confusion exist in the literature regarding vegetarianism. Traditionally, a vegetarian or vegan diet was considered low in certain micronutrients (iron, zinc, calcium, iodine, vitamin A, B2, B12, D), as well as protein, omega-3 fatty acids, and total energy needs. However, a vegetarian diet typically contains higher complex carbohydrates, dietary fiber, magnesium, nitrates, folic acid, vitamin C and E, carotenoids and other phytochemicals which may offer certain performance benefits to the athlete. This review summarizes the current literature on the benefits of a vegetarian diet specific to the athlete, clarifies nutritional requirements, and provides insight on the potential performance benefits. With proper meal planning, an athlete can meet all their nutritional needs with foods derived from plants without any loss in physical performance.
Keywords : vegetarian, vegan, diet, athlete, nutritional requirements

Introduction

In recent years, there has been growing interest in vegetarian and vegan diets, not only in the general public, but the athlete population as well. About 3.3% of Americans report being vegetarian, and 46% of these individuals are vegan[1,2]; however, the overall prevalence of vegetarian athletes is largely unknown[3]. In a survey of athletes in the 2010 Commonwealth Games, 8% of the athletes followed vegetarian diets, and 1% of them reported being vegan[4]. Furthermore, vegetarianism is also growing in the young adult population, as 5% of high school students (grades 9-12) and 6% of young adults (18-34 years) report being vegetarian or vegan. In addition, there is a growing shift in recommendations for people to switch to more plant-based, whole food diets[5], increased awareness regarding animal welfare[6] and concern for environmental repercussions[7,8] if high animal protein consumption countries such as America do not change their farming practices. Last year, the documentary film “Game Changers”[9] received wide media attention on the potential benefits of “plant-based” (vegetarian) diets for athletes, but also received criticism for possible sensationalism and pseudoscience[7,10]. Unfortunately, because of the variability in vegetarian diets (e.g., vegetarian, vegan, lacto-ovo, whole foods diets, raw foods diet) there are no high-quality studies on the effects of the vegetarian diet overall in athletes. Most studies in athletes examine specific plant foods or single-dose plant food supplementation, not the effects of a vegetarian diet as a whole. With the recent popularity and increased media visibility of vegetarian and vegan diets, however, clinicians treating athletes need to be aware of the latest science and recommendations. This review summarizes current available literature on vegetarian and vegan diets specific to the athlete. A background on these “plant-based” (vegetarian) diets is presented, along with a summary of key macro- and micronutrients important to athletes considering a change to a vegetarian or vegan diet.

*Correspondence: kvitale@health.ucsd.edu

Methods

A literature search utilizing PubMed/Medline was performed in April 2020 including the past 10 years prior. No data restrictions were employed for language, date, subject age, or article type. Keywords included vegan, vegetarian, plant-based, athlete, exercise, nutritional requirements, and performance.

An initial search including vegan/vegetarian and athlete/exercise produced 78 potential articles. Studies that did not include relevance to exercise or athletes, and studies that involved patients or medical diseases were excluded. Abstracts of conference proceedings, as well as in-vitro and animal studies were also excluded. Additionally, manual searching of references of the above retrieved articles and additional expanded search of NCBI databases, including NLM Catalog, PubMed Central (PMC), and Google Scholar yielded 25 additional articles; duplicates were removed. Fig. 1 represents the PRISMA search strategy.

A total of 50 studies met eligibility criteria. Due to significant methodological heterogeneity, pooling of data and a systematic review was impossible; therefore, a narrative review was performed.

Vegetarian and vegan diets for athletes

A vegetarian diet is defined as a diet that does not include any animal meats, including red meat, poultry and seafood[11]. Variations include lacto-, ovo-, lacto-ovo, or pesco-vegetarian which are diets that include dairy, eggs, both dairy and eggs, or fish, respectively. Vegan diets exclude all animal-derived products and byproducts including meat, fish, seafood, dairy, eggs, and honey[11]. While there are minor differences in lacto-, ovo-, and lacto-ovo vegetarian diets, vegetarians in general tend to consume slightly more calcium, phosphorous, vitamin D and vitamin B12 than vegans due to the consumption of dairy products[3,5,11]. Vegans are traditionally considered to be at risk for low protein, creatine and carnitine[3,11] and risk low EPA and DHA omega-3 fatty acid intake[6] due to lack of eggs and seafood. All vegetarian diets (vegan and the above vegetarian variations)[3,5,11] need to ensure adequate intakes in protein, iron, zinc, calcium, vitamin A, vitamin B12, omega-3 fatty acids EPA and DHA intake and iodine, as well as vitamin D and overall caloric intake[6]. Table 1 outlines key differences in these diet variations in terms of potential nutrient deficiencies.

Vegetarian diets may lower risk of chronic diseases such as cardiovascular disease, diabetes, obesity, hypertension, and even cancer mortality[11,12]. Although chronic disease prevention may not be the primary concern of an elite athlete, it is proposed that these same diets may enhance an athlete's performance and/or speed recovery from intense or strenuous exercise bouts[3,13,14].

This is due to several potential reasons. Some authors feel the higher intake of complex carbohydrates, dietary

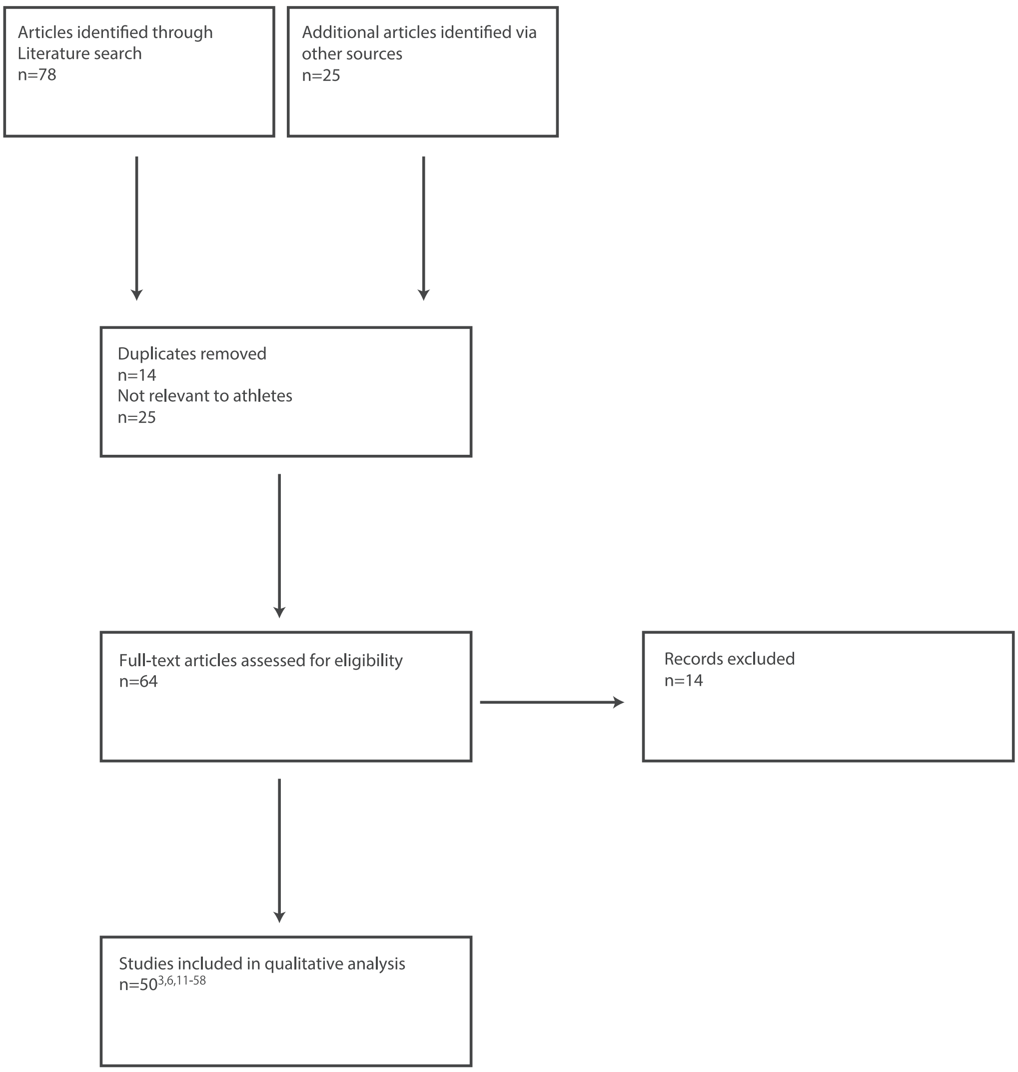

Fig. 1 PRISMA flow diagragm search strategy

Table 1. Vegetarian vs. Vegan Diet Considerations

Pesco-ovo vegetarian	Lacto-ovo vegetarian	Vegan	All vegetarian diets
Adequate omega-3 fatty acids EPA and DHA from fish	May have adequate B12 intake compared to vegans; Better omega-3 fatty acid EPA and DHA intake from eggs compared to vegans; Higher calcium, phosphorous, vitamin D and B12 from dairy products than vegans	At risk for low protein, creatine and carnitine; risk low omega-3 fatty acids EPA and DHA intake due to lack of eggs or seafood; Lower B12 and may need supplementation	All vegetarian diets (including vegan) at risk for low protein, iron, zinc, calcium, iodine, vitamin A, vitamin B2, B12, D, omega-3 fatty acids EPA and DHA intake, and overall caloric intake

fiber, magnesium, folic acid, vitamin C and E, carotenoids and other phytochemicals consumed by vegetarians[15,16] may improve performance[3]. The increased carbohydrate intake may promote better glycogen storage[14,17]. The overall increased antioxidant and other phytochemical intake from foods derived from plant sources may enhance the antioxidant system to offset the increased exercise-induced oxidative stress in elite athletes and potential environmental oxidative stresses, including altitude and prolonged sun exposure[18,19]. Another advantage of vegetarian diets is that the antioxidants derived from whole foods are generally favored over antioxidant supplements in terms of effectiveness[20].

It is also suggested that plant-based diets reduce inflammation and blood viscosity, improve arterial flexibility and endothelial function[14]. This may improve vascular flow, tissue oxygenation, and cardioprotection[14,17] for the endurance athlete that may be at higher-than-average risk for atherosclerosis and myocardial damage[21-24]. There are even studies suggesting that, due to the slight alkalinizing effect on serum during exercise[25], foods derived from plants may induce an ergogenic effect by improved buffering of acid production from intense exercise[26].

Another ergogenic benefit includes the high nitrate content in plants. Since a landmark study in 2007 showing decreased oxygen cost during submaximal exercise[27], several studies have demonstrated how nitrate-rich plant foods (such as beets and nitrate-rich greens [e.g. spinach and arugula]) can improve performance[27,29-31]. Dietary nitrate gets converted in the body to nitric oxide, which exerts pleotropic effects pertinent to athletes, including improved vasodilation, blood flow and oxygen regulation in muscle, mitochondrial function, and overall muscle contraction/relaxation[28-30]. Cumulatively, these effects can improve muscle economy during exercise, improve efficiency and mitigate fatigue, decrease cardiorespiratory effort at submaximal workloads, and improve exercise (e.g. cycling time trial) performance[29-33].

Lastly, single dose supplementation with plant-based products may also improve performance[15,34,35]. In a recent novel study, a single dose of fermented soy during a 20-km time trial cycling race improved cyclists' times to race completion, lowered average heart rates, and had significantly improved power outputs[34]. It is believed these performance benefits were due to the isoflavones found in soy, improving vascular endothelial relaxation, increasing limb blood flow, and decreasing cardiac demand. These isoflavone-induced effects would not be seen in animal-based protein sources. Another study has shown soy supplementation also improves time to exhaustion in prolonged endurance exercise[35], due, it is believed, to soy's high antioxidant capacity. This study was the first of its kind to show improved race performance times and reduced heart rates.

Conversely, there have been conflicts in research and an overall misunderstanding in the literature concerning vegetarianism[15], especially regarding nutritional deficiencies. Traditionally, vegetarians were considered to have inadequate intakes in protein, iron, zinc, calcium, vitamin A, vitamin B12, omega-3 fatty acids EPA and DHA, and iodine[15], as well as vitamin D and overall caloric intake[6]. However, several studies demonstrate these deficiencies are typically due to poor meal planning[15] rather than inadequate nutrient content in a vegetarian diet. In the following sections, select macronutrients and micronutrients (including a special section on protein) are reviewed with recommendations specific to the plant-based athlete. Also, performance considerations are provided for the elite or professional athlete interested in following a vegetarian or vegan diet.

Macronutrients

Carbohydrate. Carbohydrates can be an important component to an endurance athlete's diet as they are necessary for glycogen repletion if the athlete undergoes exhaustive exercise. Due to the inherent nature of carbohydrate-rich foods in a vegetarian diet, a vegetarian athlete is likely able to meet typical carbohydrate needs[36]. Although some sports such as power or skill-based sports require less carbohydrate intake (3-5 g/kg/day) and not a concern, even endurance and ultra-endurance athletes following a vegetarian diet can easily meet carbohydrate loading ("carbo loading") and overall high carbohydrate needs (up to 8-12 g/kg/day) with a plant-based diet[36].

One precaution if an athlete switches to a vegetarian diet is the potential risk of consuming too much carbohydrate compared to their previous intake– this can have a negative impact on body composition, and therefore performance, in some sports. For example, when athletes exchange an animal source of protein for a plant source (e.g. chicken for black beans) there is an associated change in nutrient profile resulting in higher carbohydrate per gram of beans compared to chicken. Weight class athletes and athletes in which excess body fat negatively impacts performance and competition results (e.g. running, jumping, diving, gymnastics, aesthetic sports) need to be aware that plant-based protein sources tend to increase carbohydrate and fat to their total intake. Appropriate planning and education on the differences in plant vs. animal-based protein sources is recommended to ensure an optimal range of carbohydrate intake.

Fat. Dietary fat can provide energy during prolonged exercise, if glycogen stores are depleted, and aids in fat-soluble vitamin absorption. Athletes should follow current public health guidelines to ensure adequate fat intake[36,37], since athletes who restrict fat intake to <20% of total energy can be low in fat-soluble vitamins and essential fatty acids[36]. Lacto-ovo vegetarians and pesco-vegetarians (fish consumption with vegetarian diet, also called pescetarianism) typically consume adequate essential fatty acids; however strict vegans may be low in the omega-3 fatty acid eicosapentaenoic acid (EPA). Even though conversion of alpha-linolenic acid (ALA) to EPA and docohexaenoic acid (DHA) in humans is inefficient, current research suggests vegan athletes can meet EPA/DHA requirements by adequate intake of ALA[12]. Vegetarian athletes may also opt for DHA-rich microalgae supplements[38].

Overall, adequate energy intake is important for any athlete, regardless of whether they eat foods derived from animal and/or plants. Athletes not meeting total energy requirements may suffer impaired performance, recovery, and may experience health consequences such as weight loss, sarcopenia, low bone mass, chronic fatigue and illness[3,36]. Plant-based athletes may risk inadequate caloric intake due to the high-fiber and low caloric density foods contained in a plant-based diet. However, frequent meals, selecting energy-dense foods, and limiting excessive high-fiber foods should help meet energy needs in a vegetarian and vegan athlete.

Protein. Protein intake is often the most controversial aspect of vegetarian and vegan diets for athletes. In addition, protein supplements are a multi-billion-dollar market with widespread use in sports[39], and many athletes follow a high-protein diet[39]. Traditional recommendations indicate high-performance athletes require 1.2-2.0 g/kg/day of protein according to sport category[36], however newer recommendations suggest 1.6 g/kg and up to 2.2g/kg depending on type of sport and goals[40]. Additionally, protein timing may favorably impact athletes. Intake of a 0.25-0.3 g/kg dose within the 0-2 hour post-exercise window can stimulate muscle protein synthesis (MPS)[36,41]. Alternatively, 0.4 g/kg 4 times a day[40] may be a simpler way to achieve protein needs. This latter approach may be more practical to high-level athletes who usually train multiple times a day - the window after exercise may be less important compared to steady intake throughout the day to cover the times after each training session. Regardless of protein source, this dose should have a high concentration of not only branched-chain amino acids, such as leucine to stimulate MPS, but approximately 10g of the essential amino acids (EAA) to maximize MPS[36,41,42].

There is little evidence that protein requirements in vegetarian athletes are any different than omnivorous athletes[3]. However, athletes who consume plant-based protein sources need adequate EAA and leucine intake to ensure appropriate MPS. Leucine (at least 2.5g doses) has been shown in multiple studies to be a powerful activator of mTORC and other signaling proteins involved in MPS[36,41,42]. While animal-based whey protein is high in leucine and classically considered a preferential source for omnivorous athletes, soy, pea, brown rice, potato, and corn all can provide leucine requirements[43]. However, individual plant leucine amounts vary. Due to the greater leucine content of corn, 20 g of corn protein would need to be ingested to provide 2.7 g leucine. The dose of other individual plant-based proteins would need to be increased [e.g. 33 g (potato), 37 g (brown rice), 38 g (pea), 40 g (soy)] to achieve a similar leucine content as corn[43]. Therefore, athletes should incorporate varied plant-based sources of protein to obtain appropriate leucine and EAAs.

Individual plant-based protein sources may lack adequate amounts of certain amino acids such as leucine, methionine, and lysine. The relative shortage of these amino acids may contribute to potential lower anabolic capacity of plant-based proteins compared to animal sources[43]. Other possible reasons for lower anabolism may be due to the lower digestibility and absorption (about 10-15% lower) of plant-based proteins, greater splanchnic extraction and subsequent urea synthesis[44] and shuttling of plant protein towards oxidation rather than MPS[45], which may be related to lower concentration of certain EAA in plant-based proteins[44]. However common food combinations e.g. rice and beans, beans and nuts/seeds [hummus], nut butter sandwiches typically are complementary and can provide a complete profile of all EAA (e.g. grains are low in lysine but high in methionine, legumes are low in methionine but high in lysine, and corn and potatoes are high in leucine)[43]. This is further supported by a recent review pointing out that protein-rich plant foods are sufficient for human requirements, and the question of amino acid deficiency in plant foods has been substantially overstated[5]. Furthermore, the once-popular recommendation that one needs to combine protein sources in the same meal to achieve a complete EAA profile at each feeding no longer appears necessary, as long as the daily total intake is adequate[8,12,43,46]. This allows more flexibility in meal-planning for an athlete that consumes only plant protein sources.

There are numerous studies and reviews suggesting cardiovascular disease risk and metabolic syndrome risk may be reduced by incorporating more plant-based protein sources[47,48], as well as all-cause and cardiovascular mortality[49]. However, to date there are limited high-quality studies specifically examining animal vs. plant-based protein regarding athletic performance. A recent study investigated 25g of either pea or whey protein supplementation twice a day in a double-blind randomized placebo-controlled trial and showed no difference in muscle strength or thickness[50]. Another study compared 24g of whey vs. pea protein supplementation taken before and after exercise on training days and in-between meals on non-training days during an 8-week high-intensity functional training program[51]. There were no differences in body composition, muscle thickness, strength (thigh muscle peak force or rate of force development), or performance (benchmark workouts of the day)[51]. However, these preliminary studies have limitations, since they were not conducted on elite, professional, or Olympic/Paralympic athletes; and in some cases, the sample size is quite small. While preliminary, they do suggest there are no significant differences for athletes in terms of muscle size, muscle strength, or performance when consuming whey vs. pea protein supplements, although more studies are needed.

Micronutrients

Vegetarian athletes should emphasize the adequate intake of certain micronutrients, as several of these have been shown to be either less abundant or less efficiently absorbed compared to animal sources[3]. These include iron, zinc, calcium, vitamin A (according to one study[15]), vitamin B2, vitamin B12, iodine and vitamin D[6,15]. In contrast, vegetarian diets typically have higher concentrations of folic acid (vitamin B9), vitamin A, C, E, and K, and carotenoids[12,16], as well as potassium and magnesium[12,15,16]. The following sections explain important vitamin and mineral issues faced by vegetarian athletes; Table 2 provides a summary of the important differences in vegetarian diets compared to omnivorous diets.

Vitamins. An advantage of a vegetarian diet is the reported higher intake of folic acid (vitamin B9), vitamin C and E, and carotenoids[16]; this higher intake has been proposed to improve performance[3]. Plant-based diets also typically have plentiful sources of the vitamins A and K as well[12]. A vegetarian athlete typically contains adequate amounts of these micronutrients and supplementation therefore is generally not needed[52].

Furthermore, as mentioned above, the overall increased antioxidant effect from the higher intake of these vitamins may offset the increased exercise-induced oxidative stress in elite athletes, and potential environmental oxidative stresses such as altitude and prolonged sun exposure experienced by athletes[18,19]. Another advantage is that the antioxidant vitamins derived from whole foods are generally favored over antioxidant supplements in terms of effectiveness[20].

However, there are a few concerns regarding micronutrient vitamin intake. Traditionally, vegetarians are considered to have potential inadequate intakes of vitamin A (according to one study[15]), B2 and B12, as well as vitamin D[6,15]. Vitamin D supplementation may be required if an athlete lives in an area (or follows a lifestyle) with limited natural sunlight exposure (e.g., athletes who use sunscreen regularly when training outdoors, practice indoors, have darker skin color). Strict *vegan* athletes may not consume adequate vitamin B12, found in animal-derived foods[12]. Fortified foods or B12 supplementation is recommended for vegans[12], whereas lacto-ovo vegetarians generally obtain sufficient amounts.

However, studies demonstrate these deficiencies are usually due to poor meal planning[15] rather than inadequate nutrient content in a vegetarian diet. Careful meal planning can avoid these pitfalls in the plant-based athlete's meal plan. Obtaining these micronutrients via natural or fortified foods is recommended; however, plant-based athletes may opt for supplementation due to convenience[12,36].

Minerals. In contrast to vegetarians often showing a higher intake of multiple vitamins, the only minerals reported to be higher in vegetarians is potassium and magnesium[12,15,16]. A vegetarian athletic diet typically contains adequate amounts of these micronutrients and supplementation is generally not needed[52]. Furthermore, these are critical minerals to athletes and higher intakes are purported to improve performance[3].

Traditionally, vegetarians are considered to have inadequate intakes of iron, zinc, calcium, and iodine[15]. However, as with vitamins, studies show these mineral deficiencies are often due to poor meal planning[15] rather than inadequate nutrient content in a vegetarian diet. Although, a few considerations are worth mentioning. Non-heme iron and zinc are better absorbed with vitamin C and should be taken together, and single high-dose mineral supplementation should be avoided, as high doses of one mineral may compete for absorption with another[12]. Certain food preparation techniques such as soaking, sprouting, and fermenting/leavening also reduce the phytate content, which binds minerals and can prevent absorption[12]. High oxalate content in certain greens (e.g. spinach, chard) may also bind and limit availability of calcium[52]. Lastly, iodine may be adequate according to geographic region, but supplementation is recommended if an athlete lives in a region with iodine-poor soil, or

Table 2. Macronutrient and micronutrient differences of vegetarian diets

	Potentially low in vegetarian diets	Considered high in vegetarian diets
Macronutrients		
Carbohydrate		Higher; may promote glycogen storage
Fat	Lower, especially omega-3 fatty acids EPA and DHA if vegan	
Protein	Lower; especially leucine and other EAA	
Micronutrients: Vitamins		
Vitamin A carotenoids	Lower in one study	Higher in several studies
Vitamin B2	Lower	
Vitamin B9 (folate)		Higher
Vitamin B12	Lower; vegans may need supplementation	Lacto-ovo vegetarians may have adequate intake
Vitamin C		Higher
Vitamin D	Lower; supplementation may be needed if low sunlight exposure, training indoors, darker skin color	
Vitamin E		Higher
Vitamin K		Higher
Micronutrients: Minerals		
Magnesium		Higher; may improve performance
Potassium		Higher; may improve performance
Iron	Lower; Non-heme iron better absorbed with vitamin C	
Zinc	Lower; better absorbed with vitamin C	
Calcium	Lower; High oxalate content in certain greens may limit calcium absorption	
Iodine	Lower; supplementation may be needed if iodine-poor soil, or athletes uses iodine-free salts	
Other:		
Fiber		Higher
Antioxidants		Higher; may offset increased oxidative stress
Phytochemicals		Higher; may offset inflammation
Nitrates		Higher; may improve performance
Isoflavones (in soy)		Higher; may improve performance
Creatine	Lower; may affect high-intensity exercise, supplementation considered	
β-alanine	Lower; supplementation may be consider if power sport	
Carnosine	Lower; supplementation may be consider if power sport	
Total Calories	Lower; due to the high-fiber and low caloric density foods contained in a plant-based diet	

uses only iodine-free salts[12,52]. These nutrients can easily be obtained with a simple well-balanced diet, and as mentioned above, these deficiencies typically occur more commonly due to poor meal planning[6] rather than poor food sources.

Other micronutrients such as nitrates, antioxidants, polyphenols, isoflavones, and other phytochemicals.

Plant-based diets typically have plentiful sources of nitrates, antioxidants, polyphenols, isoflavones, and other phytochemicals[12]. The increased levels of phytochemicals consumed by vegetarians[15,16] may improve performance[3]. The overall increased phytochemical intake from plant sources may enhance the antioxidant system and offset the increased exercise-induced oxidative stress experienced by elite athletes[18,19].

Another ergogenic benefit mentioned above is derived from the high nitrate content in plants. Several studies have demonstrated how nitrate-rich plant foods can improve performance in athletes[27,29-31]. Nitric oxide can improve blood flow and oxygen regulation in muscle and improve mitochondrial function[28-30]; cumulatively, these effects can improve muscle economy and efficiency, reduce fatigue and cardiorespiratory effort at submaximal workloads, and improve performance[29-33].

Finally, the isoflavones found specifically in soy can improve vascular endothelial relaxation, increase limb blood flow, and decrease cardiac demand[15,34,35]. While this would be specific to the athlete who eats soy as part of their diet, studies have shown these isoflavone-induced effects can improve power outputs and cyclists' times to race completion, as well as lower average heart rates[34].

Performance Considerations

Specific to the athlete, there has been skepticism regarding vegetarian diets and performance compared to traditional omnivorous diets. However, vegetarian-based diets compared to omnivorous mixed diets (when matched for total energy, micro- and macronutrient intake appropriate to support the needs of the athlete) have shown no distinguishable differences in physical performance in several randomized trials and reviews[53-55] in terms of strength/power, aerobic exercise and anaerobic exercise performance. In addition, specifically animal vs. plant protein supplementation has shown no strength, muscle size, or performance differences[50,51].

However, there are a few legitimate concerns. Female and male athletes following vegetarian and vegan diets may be at increased risk of (non-anemic) iron deficiency that may limit endurance performance[17,56], and needs to be carefully accounted for in an athlete's dietary choices and monitored with bloodwork as clinically indicated. Male and female athletes who rely primarily on plant-based proteins may also have lower mean muscle creatine concentrations compared to their omnivore counterparts, which may affect supramaximal (repeated high-intensity bouts, high intensity interval training) exercise performance[56]. Some research suggests that creatine and β-alanine supplementation may be beneficial to vegan athletes who engage in power sports, since they may have lower creatine and muscle carnosine levels[6]. One study has suggested vegetarians were likely to experience greater performance increments, after creatine loading, in short high-intensity sports that mainly rely on the adenosine triphosphate/phosphocreatine (ATP/CP) system for energy[56]. It is important to note that the majority of elite athletes perform some type of strength training which relies on this energy system; even endurance athletes regularly utilize the ATP/CP system and may benefit from elevated levels of muscle creatine. And, in a very recent study in soccer players, creatine supplementation seems to have shown some improvement in cognitive performance[57], warranting further investigation into the brain phosphocreatine's effects on mental fatigue. While there have been no studies specifically in vegetarian or vegan athletes regarding brain creatine levels, this finding is of importance to athletes who may consider creatine supplementation. Further studies are needed.

The overall exercise capacity of vegan, lacto-ovo-vegetarian and omnivorous recreational runners was examined in a recent study[58]. Vegan and lacto-ovo-vegetarian runners were compared to omnivorous runners and performed a maximal exercise stress test to exhaustion. All three groups had comparable training frequency, training time, and running distance. There were no differences in terms of maximal power output or lactate levels, and the authors concluded that any of the vegetarian diets might be suitable alternatives for recreational athletes compared to omnivorous diets.

However, this previous study presumes that the athletes all had similar energy availability. As mentioned in the carbohydrate section, vegetarian athletes usually can meet carbohydrate needs due to the inherent carbohydrate-rich nature of plant-based foods. Some may assume therefore they are able to meet overall energy needs as well. However, on the contrary, some athletes who primarily eat plant-based foods may struggle to maintain an appropriate energy balance due to more restrictive eating patterns. Although energy *balance* is considered important (comparing energy intake to energy expenditure), energy *availability* is most important to athletes. Energy availability is the amount of dietary energy remaining after exercise, available for other physiological functions such as growth, muscle recovery, and homeostasis[59]. Athletes who eat primarily plant-derived foods may be at risk of low energy availability if their total daily intake is insufficient. For example, one of the key concerns of vegetarian diets is the high fiber content, which may lead to early satiety and appetite blunting[60] resulting in potentially too few calories consumed to support energy expenditure from training. Also, besides consuming more high-fiber foods, vegetarian athletes may choose less energy-dense foods resulting in undereating[61]. Another challenge when transitioning to plant-based foods is an athlete may exclude certain foods (i.e. animal-based foods) without replacing the nutrients from another source. These factors can lead to a decrease in total daily calories, low energy availability, energy imbalance, and poor performance in the vegetarian athlete[59].

Furthermore, low energy availability underlies the female athlete triad, male athlete triad, and relative energy deficiency in sport (RED-S) syndromes[59]. The health concerns associated with these low energy availability syndromes (e.g. menstrual and cardiovascular dysfunction, compromised bone health) can also contribute to impaired sports performance[59]. Therefore, it is paramount for athletes to achieve proper energy balance and energy availability. A detailed meal plan designed to support the athlete's training volume, intensity, and duration is key to avoiding an unwanted energy imbalance.

Lastly, in regard to performance considerations, Table 3 summarizes key recommendations for athletes including macronutrient breakdown[32]. While specific macronutrient

Table 3. Key recommendations for macronutrients, hydration, and supplements for athletes *(exercise duration is listed in italics within parentheses). Adapted from: "Nutrition and supplement update for the endurance athlete: review and recommendations" by Vitale, K. and Getzin, A., 2019, Nutrients, 11(6), p.1289. Copyright 2019 by Kenneth Vitale. Reprinted with permission by author.*

Nutrient	Daily Requirements	Pre-Exercise	During Exercise	Post-Exercise
Carbohydrate	5–7 g/kg/day *(1 h/day)* 6–10 g/kg/day *(1–3 h/day)* 8–12 g/kg/day *(4≥h/day)*	6 g/kg/day *(<90 min)* 10–12 g/kg/day *(> 90 min)* + 1–4 g/kg (1–4 h prior to event)	30–60 g/h *(<2.5 h)* 60–70 g/h *(>2.5 h)* 90 g/h *(>2.5 h, if tolerable)*	8–10 g/kg/day (first 24 h) 1.0–1.2 g/kg/h (first 3–5 h) or 0.8 g/kg/h + protein (0.3 mg/kg/h) or caffeine (3 mg/kg)
Protein	1.4 g/kg/day 0.3 g/kg every 3–5 h	0.3 g/kg immediately prior (or post–exercise)	0.25 g/kg/h (if high intensity/eccentric exercise)	0.3 g/kg within 0–2 h (or pre-exercise)
Fat	Do not restrict to <20% total caloric energy Unclear role of CLA, omega-3, MCT supplements Consider limiting fat intake only during carbohydrate loading, or pre-race if GI comfort concerns			
Water	Try initial hydration plan at ~400–800 mL/h; Adjust according to individual athlete variations (sweat rates, sweat sodium content, exercise intensity, body temperature, ambient temperature, bodyweight, kidney function) Follow thirst mechanism, monitor parameters (bodyweight, urine color)			Replace fluid with 150% of fluid lost
Sodium	Try initial sodium plan at 300–600 mg/h if high sweat rate (>1.2 L/h), subjective "salty sweater," or prolonged exercise >2 h Adjust intake according to individual athlete variations (sweat rates, sweat sodium content, exercise intensity, body temperature, ambient temperature, bodyweight, kidney function)			Improved water repletion observed with >60 mmol/L sodium content (~1380 mg/L)
Nitrates	300–600 mg of nitrate (up to 10 mg/kg or 0.1 mmol/kg) or 500 mL beetroot juice or 3–6 whole beets within 90 min of exercise onset Consider multi-day dosing e.g., 6 days of a high-nitrate diet prior to event			
Antioxidants	Avoid prior to exercise to maximize training adaptation Take prior to exercise only if recovery needed within 24 h Many options: whole foods, dark berries, dark greens, green tea e.g., 8–12oz tart cherry juice twice a day (1oz if concentrate) 4–5 days prior and 2–3 days after event e.g., green tea extract (270–1200 mg/d)			
Caffeine	3–6 mg/kg taken 30–90 min prior to exercise Consider "topping-up" every 1–2 h as needed ≥9 mg/kg does not further enhance performance, may have undesirable side effects, + drug test ≤3 mg/kg can also be ergogenic without side effects			3 mg/kg with carbohydrate enhances glycogen repletion
Probiotics	*Lactobacillus* and *Bifidobacteria* may help with upper respiratory and/or GI symptoms			

amount and timing recommendations based on duration of exercise are outside the scope of this manuscript, this table concisely summarizes carbohydrate, protein and fat requirements, and additionally provides key information regarding other nutrients relevant to athletes such as sodium, water, nitrates, caffeine, and whether or not a vegetarian athlete chooses probiotic supplementation.

Conclusion

With proper planning, athletes can achieve all their nutritional needs via a vegetarian or vegan diet. There are certain considerations in terms of macro- and micronutrient intake specific to a plant-based diet, such as iron, zinc, calcium, vitamin A, vitamin B2 and B12, iodine, vitamin D, and overall energy intake. Protein requirements are no different in a vegetarian athlete compared to an omnivorous athlete, as long as a plant-based athlete can meet EAA (including leucine) requirements and total protein intake throughout the day. While more studies are needed, plant-based diets may even provide certain health and performance benefits compared to omnivorous diets. With the right meal planning an athlete can not only meet all nutritional requirements with plant-based foods, but also enjoy similar strength/power, aerobic and anaerobic exercise performance.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

Author Contributions

KV conceptualized, designed, developed the theory of the manuscript, performed literature review and background data collection, and wrote the manuscript. SH revised the manuscript, provided critical feedback, direction and planning of the manuscript, and made critical contributions. Both authors read and approved the final manuscript.

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