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Superfoods: exploring sustainability perspectives between nutrient synthesizers and accumulators

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"Superfoods" is a marketing term used to describe nutrient-dense foods claimed to have health benefits due to their high concentrations of essential amino acids, vitamins, minerals, antioxidants, and other bioactive compounds. Recently, the need for healthy diets has led to increased demand for these functional foods, which have become popular among middle- and high-income groups in developed regions of the earth. Superfoods can represent a smart way to improve diets, particularly in relation to diet-related issues. However, the superfood production system, as well as the broader food production system, must be reconsidered to avoid overexploitation of soil, workers, and natural resources. This perspective explores sustainability of "superfoods" by proposing a new classification system, dividing them into "synthesizers" and "accumulators" based on their origin. The aim is to provide a framework for identifying and promoting superfoods that align with environmental and social sustainability goals, helping guide both consumers and producers toward more responsible choices in food systems. Analyzing the sources and characteristics of the main compounds found in superfoods reveals that most of them come from plants or bacteria, rather than animal origins. Since animal-based food production is one of the largest contributors to greenhouse gas emissions in the agro-food sector and a major driver of deforestation and water use, it is advisable to focus on plant organisms as the primary and direct sources of beneficial compounds. Nevertheless, great attention must be paid to vegetable crops that imply an overexploitation of soil and water and induce the degradation of entire ecosystems.

KEYWORDS

nutritional sustainability, functional foods, environmental impact, plant-based diets, agroecological practices

Introduction

The term "superfood," originally coined in the 60s to describe foods capable of fighting malnutrition (Jelliffe, 1966), has seen a significant change in meaning since the 2000s, becoming a target for marketing strategies. Nowadays, no specific scientific standards define what constitutes a superfood, but the term generally refers to a group of nutrient-dense foods and bioactive compounds with positive effects on human health.

In various religious traditions, there are narratives of foods with "miraculous effects". A well-known example is manna, described in the Old Testament as food provided by God to men during the exodus from Egypt. Manna is actually the sugary sap of plants of the genus *Fraxinus*, in particular *Fraxinus ornus* (Włodarczyk, 2007). Foods such as honey, almonds and olives are mentioned in the Bible and appreciated for their nutritional properties, while the Quran contains accounts of miracles linked to food performed by prophets, and Hindu scriptures recount divine food in times of need.

Aside from the metaphysical aspects of recalling symbolic episodes or imitating the Divine, there are certainly traditions of foods that lie outside of sacred texts. For instance, traditional balsamic vinegar of Modena has been administered by the spoonful to children, as well as cooked must (made from grapes or figs), fruit compotes and preserves are other examples of foods enjoyed on special festive occasions (Montevecchi et al., 2010; Vasile Simone et al., 2013).

The variety of foods considered superfoods varies globally. In some cultures, local berries and fruits are preferred, while in others, fatty fish or whole grains are valued. This diversity shows that the definition of superfood fits the dietary needs of each culture.

In the most current sense, from a compositional perspective, a superfood is characterized by its “high nutritional density,” in terms of vitamins and other essential nutrients (e.g., fatty acids, amino acids), minerals, soluble fibers, amino acid analogues like L-theanine (Montevecchi, 2005), as well as bioactive compounds with antioxidant activity (Manach et al., 2004). Superfoods consumption is often associated with a reduction in the risk of chronic diseases, non-communicable diseases, and support for the immune and cognitive systems (Rasouli et al., 2017). In addition, many superfoods are minimally processed, thus maintaining nutritional quality and facilitating their integration into the daily diet.

Garlic (*Allium sativum*) and ginger (*Zingiber officinale*) are widely regarded as superfoods due to their health properties. Garlic, rich in allicin, has antithrombotic, antimicrobial and anti-inflammatory effects, contributing to reduced LDL cholesterol and blood pressure (Bongiorno et al., 2008). Ginger, containing gingerol, relieves pain and inflammation, improving motor skills (Mohd and Makpol, 2019). Red yeast rice (or red fermented rice), rich in monacolin K, is another superfood known for its effect in controlling LDL cholesterol (EFSA Panel et al., 2018).

In recent times, the pandemic has increased interest in foods capable of boosting immunity and protecting against pathogens. This list includes foods such as ginseng (*Panax* sp. pl.), eleuthero (*Eleutherococcus senticosus*, also known as Siberian ginseng or devil’s bush), echinacea (*Echinacea* sp. pl.), goji berries (*Lycium barbarum*), aloe (*Aloe vera*), turmeric (*Curcuma longa*), gingko (*Ginko biloba*), or individual molecules such as quercetin (a flavonoid found in many plants) and chloroquine (a synthetic derivative of quinine, a natural alkaloid originally extracted from the bark of the Andean plant *Cinchona*, known and used as a medication with antipyretic, antimalarial and analgesic properties). These foods are considered as potential panaceas in extreme situations. In this context, superfoods can represent not only a nutritional option, but also a way to address public health challenges.

The global superfoods market is projected to grow from a minimum estimated size of 155.2 billion dollars in 2022 to a maximum of 344.9 billion dollars by 2033, with a compound annual growth rate (CAGR) ranging between 4.0% and 10.2% during the forecast period, depending on the information source (Globenewswire.com, 2025; Grandviewresearch.com, 2025; Marketresearch.com, 2025; Market.us, 2025; Mordorintelligence.com, 2025).

Several countries dominate the global market, each excelling in the production of specific superfoods due to their agricultural traditions and favorable climates. The United States, within the largest market of North America, leads in cultivating and innovating with superfoods like kale, quinoa, and blueberries. Peru plays a critical role as a leading exporter of quinoa and Andean crops such as maca root. China, part of the fastest-growing market in Asia-Pacific, is the top producer of goji berries and spirulina, supplying most global exports. India is a major player in moringa and turmeric production, driven by its Ayurvedic heritage and government support for exports. Japan is renowned for matcha green tea, a growing favorite in Western markets.

Beyond economic projections, it is crucial to consider that the growing popularity of superfoods necessitates assessing their production impacts on environmental, economic, and social sustainability. This perspective paper aims to establish a novel classification system that distinguishes superfoods based on their origin—synthesizers or accumulators. By analyzing these categories, we provide insight into how superfoods can be produced and consumed responsibly, contributing to sustainable dietary practices and minimizing adverse impacts on natural resources and ecosystems.

Sustainability in global consumption

Although superfoods are currently experiencing great popularity, it is crucial to reflect on the potential issues associated with their global consumption, as seen with other foods or raw materials. Growing demand can lead to unsustainable agricultural practices and, in turn, a reduction in biodiversity. Therefore, responsible consumption and the choice of local and sustainable superfoods can contribute not only to a healthy diet but also to a more resilient use of the planet’s resources.

A prominent example is the case of palm oil (*Elaeis guineensis*), whose growing demand has led to dramatic changes in Southeast Asian ecosystems, with severe consequences for biodiversity and human rights. Deforestation for its cultivation has triggered conflicts with indigenous communities and contributed to the climate crisis (Mukherjee and Sovacool, 2014; Ardiansyah, 2006). Similar situations can be observed in the Amazon, where deforestation for large-scale agriculture threatens biodiversity and the wellbeing of local populations (da Silveira Bueno et al., 2021). The production of cocoa and coffee is also widely associated with issues such as child labor and deforestation (Bertrand and de Buhr, 2019).

Overfishing undermines global food security. Fish such as bluefin tuna (*Thunnus thynnus*) and salmon (*Salmo salar*) have experienced drastic population declines due to growing demand (Knudsen et al., 2020). In addition, animal welfare issues are evident in luxury foods such as “civet coffee,” obtained through invasive practices on civets (*Paradoxurus hermaphroditus*) (Carder et al., 2016). Furthermore, there has long been strong opposition to the production of *foie gras* and caviar (Skippon, 2013). The rising global food demand, driven by population growth, is causing environmental and social concerns due to the corresponding increase in the consumption of animal-based products (meat, fish, and dairy), which is projected to grow by up to 8.5% over the next decade (OECD-FAO, 2023). Since livestock and other forms of animal farming contribute significantly to greenhouse gas emissions (Poore and Nemecek, 2018), the shifting to a sustainable plant-based protein production, performed with low-impact systems, is crucial for addressing this growing demand while mitigating environmental harmful effects.

Discussion

Considering the points discussed, it is essential to classify superfoods based on principles of environmental, social, economic and ethical sustainability. It is urgent and necessary to avoid devastating aberrations such as deforestation to establish *Lycium* plantations for goji berry production, or the use of anabolic doping to achieve the "world record nutritional performance" in salmon. Moreover, it is crucial to limit the exploitation of natural resources for animal feed and farming, currently applied as the primary source of proteins production (Bryant, 2022). Gaining a deeper understanding of nutrient synthesizers and accumulators could support the food technology and production sectors in advancing a sustainable transition.

On the other hand, consumer's perceptions of synthetic molecules with bioactive properties can vary greatly depending on several factors such as culture, knowledge, health concerns, and risk perception. Synthetic vitamin C consists solely of ascorbic acid, while natural vitamin C is obtained, for instance, from the rose hips of *Rosa canina*. This fruit contains a phytocomplex that, in addition to ascorbic acid, also includes bioflavonoids, enzymes, coenzymes and other factors, that enhance the effectiveness of vitamin C. Similarly, natural vitamin E that includes tocopherols and tocotrienols–and not just alpha-tocopherol–is more effective than its synthetic equivalent (Mindell, 1991).

A synthetic substance can cause a reaction in a person susceptible to certain chemicals, while the same substance of natural origin is often better tolerated, despite having an identical chemical structure. This may be due to more gradual absorption. An emblematic example is fructose, which is widely abundant in fruit without raising significant concerns, whereas fructose used as a sweetener is universally recognized as hepatotoxic, with effects similar to ethanol (Lustig, 2013). In general, natural compounds tend to cause fewer gastrointestinal issues, and toxic reactions are less common when consumed in doses higher than recommended.

The classification proposed in this prospective article allows superfoods to be divided into two categories based on their origins:

- organisms that **synthesize** nutrients and bioactive molecules;
- organisms that **accumulate** nutrients and bioactive molecules, synthesized by the former.

In this regard, Table 1 shows a list of the main essential nutrients.

Vitamin A is essential for vision and cellular health and is mainly obtained through precursors such as beta-carotene, which is synthesized by plants, algae, and microorganisms. Animals, unable to synthesize vitamin A on their own, obtain it through their diet and store it in organs such as the liver (Rafeeq et al., 2020).

B vitamins include water-soluble compounds vital for cellular metabolism, though they do not necessarily share structural or functional characteristics (Said, 2015). Plants can synthesize most vitamins of the B group, although B12 is not synthesized by plants at all and must be obtained from other sources (LeBlanc et al., 2013). B vitamins are water-soluble and are generally not accumulated in large quantities in organisms, with only limited storage possible in animal tissues.

Humans cannot synthesize these vitamins and must obtain them from the diet or from the gut microbiota, which produces some B vitamins, such as B7 or small amounts of vitamin B12 (LeBlanc et al., 2013). However, these quantities are sometimes insufficient or are produced in distal regions of the intestine (large intestine) that do not allow for adequate absorption. In addition, there are several chemical forms of vitamin B12. Cyanocobalamin (an artifact formed during extraction with papain) and hydroxocobalamin (of microbial origin) are "active" forms, while green algae and blue algae (such as cyanobacterium Spirulina) may contain pseudo-vitamin B12, a form that is not bioavailable for humans (Watanabe and Bito, 2018). On the other hand, the multicellular alga known as Nori (*Porphyra* spp.) contains an active form of vitamin B12, which can be absorbed and used by the human body (Watanabe et al., 2013).

The intake of vitamin B12 is a critical concern for those following vegetarian, and especially vegan, diets (Watanabe et al., 2014). Therefore, an interesting nutritional challenge is finding non-animal alternatives without resorting to supplements. Tempeh (fermented soybeans) is a valuable alternative source of vitamins, particularly vitamin B12. While *Rhizopus oligosporus*, the mold conventionally used in tempeh fermentation, does not synthesize vitamin B12 itself, this vitamin is typically produced by non-pathogenic bacteria, such as *Klebsiella pneumoniae* and *Citrobacter freundii*, present during the fermentation process. In addition, *Rhizopus oligosporus* increases other B vitamins, including folic acid, niacin, riboflavin, and pyridoxine, making tempeh a nutritious food choice for those seeking to boost their vitamin intake (Kårlund et al., 2020).

Ruminants, such as cows, sheep and goats can exploit microbiota in their rumen for B vitamins synthesis (Jiang et al., 2022). In contrast, in monogastric animals, gut microbial production largely occurs in areas where absorption is ineffective. Similarly, in fish and birds, vitamins of the B group must also be obtained from the diet.

Vitamin C (ascorbic acid) is an essential molecule for humans (as well as some primates, guinea pigs, and some birds) because they have lost the ability to synthesize it (Carr and Maggini, 2017). In addition, this molecule is thermolabile, meaning its source should not require drastic thermal treatments to preserve its efficacy.

The plant kingdom is the primary source of vitamin C, which accumulates mainly in fruits, leaves, tubers, and seeds. Mammals, birds (chicken and turkey), and some fish (salmon and tuna) can instead synthesize it in the liver, while mollusks and crustaceans obtain it from the diet. Vitamin C is generally not accumulated in large quantities in organisms, but is used according to metabolic needs, with excess amounts excreted via urine.

TABLE 1 Breakdown of nutrients in the human diet according to source of origin: synthesizing organisms and accumulating organisms.

Nutrients	Subcategory	Synthesizer organisms	Accumulating organisms	References
Vitamin A (retinol)		In the form of "carotenoids" precursors, such as beta-carotene in plants, algae, bacteria. Green leafy vegetables such as kale, spinach and orange/yellow vegetables, such as carrots, pumpkin, sweet potatoes, apricot, canary melon, goji berries, acai berries, fermented papaya, red vine leaves, spirulina, nori seaweed.	Animal organisms (mammals, birds, fish) can convert beta-carotene into vitamin A and accumulate it in the liver and spleen. In animals, it is also found in milk and dairy products and eggs.	Meléndez Granados (2020) and Cazzonelli (2011)
Vitamin B	B1 (thiamine)	Plants, yeast, bacteria. Brewer's yeast, wheat germ, sunflower seeds, whole grains (especially brown rice and oats), soy flour and tofu, dried peas and beans, edible seeds (walnuts, almonds, hazelnuts), asparagus, potatoes, oranges, quinoa, spirulina, goji berries, acai berries, hemp seeds. Mammalian gut microbiome.	Pork liver and beef liver, pork (lean meat), eggs, milk, and dairy products.	Putnam and Goodman (2020)
	B2 (riboflavin)	Plants, yeast, bacteria. Brewer's yeast, almonds, mushrooms (*porcini* and champignon de Paris), spinach and other green leafy vegetables, whole wheat flour and whole grains, soy and derivatives (tofu, tempeh), broccoli, peas and dried beans, quinoa, spirulina, goji berries, acai berries, hemp seeds.	Liver (beef, pork, chicken) and other offal, milk and dairy products (cheese, yogurt), eggs, oily fish (such as mackerel and sardines), beef and chicken.	Revuelta et al. (2016), Averianova et al. (2020), Bacher et al. (2000), and Bacher et al. (2001)
	B3 (niacin)	Peanuts (and peanut butter), brewer's yeast, *porcini* and other mushrooms, sunflower seeds, hazelnuts, pistachios, whole grains, lentils and other legumes, potatoes, asparagus, spirulina, acai berries.	Liver (beef, pork, chicken), chicken breast, tuna, mackerel and other oily fish, beef (especially lean cuts), pork (lean cuts), salmon.	Wolak et al. (2017) and Penberthy and Kirkland (2020)
	B5 (pantothenic acid)	Brewer's yeast, peanut and sunflower seeds, mushrooms (shiitake and champignon de Paris), avocados, legumes (lentils, beans), whole grains (whole wheat flour, brown rice), broccoli and cauliflower, sweet potatoes, corn.	Liver (beef, pork, chicken), kidneys (beef, lamb), fish (salmon, trout, herring, mackerel), eggs, milk and dairy products, chicken meat (especially breast).	Anastassakis (2022)
	B6 (pyridoxine)	Plants and bacteria. Potatoes (especially sweet potatoes), sunflower seeds, walnuts, hazelnuts, peanuts and pistachios, bananas, garlic, spinach and other leafy greens, kale, beans, chickpeas and lentils, avocados, whole grains, carrots, quinoa, shiitake mushrooms, beets, hemp seeds.	Liver (beef, pork, chicken), oily fish (such as tuna, salmon, mackerel), chicken breast and turkey.	da Silva et al. (2012)
	B7 (biotin)	Brewer's yeast, nuts (especially pecans, almonds, peanuts), sunflower seeds, avocados, whole grains (especially barley and oats), mushrooms (champignon de Paris), spinach and other green leafy vegetables, sweet potatoes, bananas, carrots, soybeans (cooked soybeans or products thereof).	Liver (beef, pork, and chicken), egg yolk, salmon, milk, and dairy products.	Zempleni et al. (2012)
	B9 (folate)	Plants and microorganisms. Brewer's yeast, leafy green vegetables, legumes lentils (cooked), black beans and chickpeas, asparagus, spinach, broccoli, avocados, rice and other whole grains, beets, sunflower seeds, romaine lettuce, strawberries, dried fruits (peanuts, walnuts, almonds), orange juice and citrus fruits (oranges, lemons), bananas, carrots, quinoa, shiitake mushrooms, hemp seeds.	Liver (beef, chicken), eggs.	Bailey and Caudill (2012) and Singh (2021)

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TABLE 1 (*Continued*) Breakdown of nutrients in the human diet according to source of origin: synthesizing organisms and accumulating organisms.

Nutrients	Subcategory	Synthesizer organisms	Accumulating organisms	References
	B12 (cobalamin)	Bacteria, archaea, algae. Among bacteria (*Propionibacterium freudenreichii*, *Pseudomonas denitrificans*, *Lactobacillus* spp., *Klebsiella pneumoniae* and *Citrobacter freundii*) Nori seaweed may contain vitamin B12, but in varying amounts and often not enough to meet human nutritional needs Algae (such as *Chlorella* spp.) and cyanobacteria (such as *Arthrospira* spp., spirulina) contain non-active analogues of vitamin B12 (pseudo-B12), which are not bioavailable to humans.	Liver (beef, pork, chicken) and other offal, mollusks (mussels, clams, oysters), fish (salmon, mackerel, tuna, sardines), octopus, beef and lamb, pork, chicken and turkey (lower quantities than beef or fish), eggs (especially the yolk), milk and dairy products (yogurt, cheese). Edible mushrooms do not synthesize vitamin B12, they must acquire it from their environment or associated microorganisms. Fermented soy (tempeh) contains vitamin B12 synthesized by bacteria, such as *Klebsiella pneumoniae* and *Citrobacter freundii*.	Watanabe and Bito (2018), Stabler (2020), Marques de Brito et al. (2023), and Kårlund et al. (2020)
Vitamin C (ascorbic acid)		Many plants are able to synthesize vitamin C. Citrus fruits, rose hips, acerola cherry, red bell pepper (raw), kiwi, strawberries, oranges, kale, cauliflower (raw), broccoli, tomatoes, blueberries, mango, papaya, spinach, blackcurrant, turmeric, spirulina, nori seaweed, goji berries, alfalfa, acai berries, beets, fermented papaya, red vine leaves.	Edible animals that can produce vitamin C do not accumulate it.	Carr and Maggini (2017) and Granger and Eck (2018)
Vitamin D		Sun-induced skin synthesis in humans. Common edible mushrooms and algae, such as shiitake (*Lentinula edodes*), oyster (*Pleurotus* spp.), and champignon de Paris, maitake (*Grifola frondose*, hen-of-the-woods); among algae kombu (*Laminaria* spp.), Tasmanian kombu (*Lessonia corrugata*) dulse (*Palmaria palmata*), wakame (*Undaria pinnatifida*) can generate significant amounts of vitamin D2 when exposed to UV radiation, whether from sunlight or specialized UV lamps. Tasmanian kombu has been reported to have measurable amounts of vitamin D3.	Accumulated in small amounts in organisms, mainly in the liver and adipose tissue, and used when necessary. Cod liver oil, cod liver, herring, salmon, mackerel, tuna, oysters, eggs (yolk).	Benedik (2022), Cardwell et al. (2018), Jungert et al. (2014), and Hughes et al. (2018)
Vitamin E	Tocopherols	Vegetable oils (wheat germ, sunflower, almonds, olives), dried fruits and edible seeds (almonds, walnuts, hazelnuts, sunflower seeds), green leafy vegetables (spinach and Swiss chard), avocados, asparagus, kiwi, tomatoes, spirulina, alfalfa, acai berries, fermented papaya.	Accumulated in small amounts in organisms, mainly in the liver and adipose tissue, and used when necessary Fish oil, cheese, eggs (yolk).	Murphy et al. (1990) and Shahidi et al. (2021)
	Tocotrienols	Tocotrienols are rarer in the diet than tocopherols. Red palm oil, rice bran oil, barley germ oil, coconut oil, whole rice bran, barley and oats (especially when consumed in whole grain form).		
Vitamin K		Vegetables and gut bacteria. Kale, spinach, Swiss chard, broccoli, parsley, soybean oil, canola oil, soybean, natto (fermented soybeans), avocados, blueberries, nori, alfalfa, red vine leaves.	Accumulated in small amounts in organisms, mainly in the liver and adipose tissue, and used when necessary. Cheese, animal liver, eggs (yolk), kefir.	Booth and Suttie (1998), Lipsky (1994), and Booth (2012)
Carotenoids	Lutein and zeaxanthin	Leafy green vegetables, such as spinach, kale, chard, and broccoli. Yellow and orange fruits and vegetables, such as carrots, pumpkin, yellow peppers, and oranges. Corn, nori, goji berries.	Eggs.	Estévez-Santiago (2016), Abdel-Aal et al. (2013), and Eisenhauer et al. (2017)

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TABLE 1 (*Continued*) **Breakdown of nutrients in the human diet according to source of origin: synthesizing organisms and accumulating organisms.**

Nutrients	Subcategory	Synthesizer organisms	Accumulating organisms	References
	Lycopene	Tomato (raw), tomato sauce, sun-dried tomatoes, tomato juice, watermelon, pink grapefruit, fermented papaya.		Khan et al. (2021) and Singh and Goyal (2008)
Essential fatty acids	Linoleic acid (omega-6)	Sunflower oil, corn oil, soybean oil, flaxseed, hemp seed, walnuts.		Gebauer et al. (2006), Wertz (2009), and Di Pasquale (2009)
	Alpha-linolenic acid (omega-3)	Flaxseed oil, chia seeds, canola oil, walnuts, soybean oil, hemp seeds.		
	Eicosapentaenoic acid (EPA) (omega-3)	Seaweed.	Fish oil (cod liver oil), salmon, mackerel, anchovies, sardines.	
	Docosahexaenoic acid (DHA) (omega-3)	Seaweed.	Fish oil (cod liver oil), salmon, mackerel, anchovies.	
Essential amino acids		Chia seeds, quinoa, spirulina, nori seaweed, goji berries, hemp seed.	Animal products (meat, fish, milk and dairy products, eggs).	Hou and Wu (2018) and Reeds (2000)
Soluble fibers	Pectin	Fruits (apples, citrus fruits) and vegetables.		Blanco-Pérez et al. (2021) and Fernandez (2001)
	Beta-glucans	Oats and barley, mushrooms (reishi, maitake).		Lam and Cheung (2013) and Vlassopoulou et al. (2021)
	Inulin and fructooligosaccharides (FOS)	Chicory root, Jerusalem artichoke, dandelion leaves (*Taraxacum officinale*), garlic, onions, leeks and asparagus, wheat bran, bananas.		Flamm et al. (2001) and Kalyani Nair et al. (2010)
	Mucilage	Flax and chia seeds.		Slavin (2005)
Polyphenols		Blueberries, kale, chia seeds, walnuts, spinach, turmeric, green tea, goji berries, alfalfa, acai berries, beetroots, fermented papaya, red vine leaves.		Aravind et al. (2021) and Wang et al. (2022)
Glucosinolates		*Brassicaceae.*		Costa-Perez et al. (2023) and Bischoff (2021)

In humans, vitamin D is mainly produced by the skin through exposure to sunlight (UV-B) from the precursor of vitamin D3 (7-dehydrocholesterol). However, vitamin D can only be accumulated in small amounts in organisms, mainly in the liver and adipose tissue (Bouillon et al., 2007).

Algae, fungi, and plants can produce vitamin D, in the form D2 (ergocalciferol) or in the form of ergosterol (precursor of D2). However, vitamin D3 (cholecalciferol) appears to be the most bioavailable and active form for humans, primarily found in animal sources.

Mammals and birds such as cow, sheep, chicken, and turkey can synthesize vitamin D when exposed to sunlight; however, supplementation may be required under conditions of low sun exposure. Fish such as salmon and tuna accumulate vitamin D through diet and light exposure, while mollusks and crustaceans do not produce vitamin D independently.

The vitamin E complex (which includes tocopherols and tocotrienols) is a potent antioxidant but is not autonomously produced by mammals, birds, or marine organisms (Brigelius-Flohé and Traber, 1999). Humans obtain it through diet, mainly from plant sources (such as olives and olive oil, seeds and their oils), as vitamin E concentrates near triglycerides, exerting an antioxidant action. Alpha-tocopherol is the most common and active form in terms of human nutritional needs.

Vitamin K must also be obtained through diet. It is essential for blood clotting and can also be synthesized by certain gut bacteria (Shearer and Newman, 2008). Plants are the main sources of vitamin K1 (phylloquinone). Vitamin K can be stored in small quantities in organisms, mainly in the liver.

Lutein and zeaxanthin are two carotenoids essential for humans, involved in the biochemistry of vision. Major dietary sources include green leafy vegetables, yellow and orange fruits and vegetables, and some grains (Johnson, 2014), as well as certain algae and bacteria (Landrum and Bone, 2001).

Mammals, birds, fish, mollusks, and crustaceans do not produce carotenoids independently but instead accumulate them from their diet.

Essential fatty acids are critical for human health and must be obtained through the diet (Calder, 2015). In addition to vegetable oils, some algae can synthesize omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), while algae thriving in freshwater (typically warmer) have very limited unsaturated fatty acid production (Santunione et al., 2024).

The ability to synthesize these fatty acids is limited in mammals, birds, and marine organisms. Fatty fish such as salmon, cod, sardines, and herring accumulate omega-3 fatty acids due to their seaweed diet. An interesting potential source of essential fatty acids could be insect larvae, as long as these fatty acids are present in their diet (Hadj Saadoun et al., 2020).

Essential amino acids (EAAs) and semi-essential amino acids must be introduced through the diet (Hou and Wu, 2018). Plants can synthesize all EAAs, although some reserve proteins (e.g., in cereals and legumes) are deficient in certain EAAs for human needs. However, combining cereals and legumes, together with a varied diet, can easily meet the EAA requirements.

Certain insects are protein-rich and capable of synthesizing all EAAs (Montevecchi et al., 2021; Miron et al., 2023). Spirulina (*Arthrospira platensis*) and chlorella (*Chlorella* sp pl.) are rich in proteins that provide a wide range of AAE (Montevecchi et al., 2022).

The human gut microbiota can produce small amounts of EAAs such as lysine and methionine. Some microorganisms used in food production, such as yeast and lactic acid bacteria, can produce proteins containing EAAs. For instance, brewer's yeast (*Saccharomyces cerevisiae*) can synthesize EAAs during the fermentation process.

Animal products contain the full range of AAEs. However, the thermal processing they undergo often leads to the degradation of specific EAAs, such as lysine (in both free and bound forms).

Plant fiber is divided into soluble and insoluble (cellulose, lignin). The main fractions of soluble fibers consumed in the diet include pectin, which help reduce cholesterol and regulate blood sugar levels by slowing the absorption of sugars and preventing spikes in blood glucose. In addition, beta-glucans are known for lowering cholesterol levels and promoting cardiovascular health. Inulin and fructooligosaccharides (FOS) are prebiotics that stimulate the growth of beneficial bacteria in the colon, improving gut health and boosting the immune system. Mucilages enhance bowel movement by hydrating the stool (Slavin, 2005).

Other sources of fiber include algae and fungi, which are known to support the immune system (Vijayabaskar and Vaseela, 2012). In addition, gut bacteria metabolize fiber into short-chain fatty acids, contributing to overall wellbeing (Louis and Flint, 2017).

Polyphenols are bioactive compounds synthesized as secondary metabolites by plants that represent their main source in the human diet (Scalbert et al., 2005; Tagliazucchi et al., 2010). Seaweed and mushrooms (shiitake and reishi) also contain beneficial polyphenols (Fernando et al., 2016; Muszynska et al., 2018).

Among the phytonutrients, glucosinolates are particularly interesting. When the cells of the Brassicaceae are damaged (for example, during chewing or processing), the enzyme myrosinase converts glucosinolates into isothiocyanates, bioactive compounds with cancer-preventive properties, particularly in the colon, breast, lungs, and prostate. They also exhibit anti-inflammatory effects, modulating inflammatory responses and reducing chronic inflammation, which is linked to various chronic diseases. In addition, they aid in detoxification by stimulating phase II enzyme activity in the liver, enhancing the elimination of toxic and carcinogenic substances, and provide cardiovascular protection by reducing inflammation and LDL oxidation (Halkier and Gershenzon, 2006; Herr and Büchler, 2010).

Microbiota (probiotics, prebiotics, and post-biotics)

The gut microbiota is an ecosystem of microorganisms that both collaborate and compete, contributing to the overall health and wellbeing of the human host. Their balance can be modulated through specific dietary components known as probiotics, prebiotics, and postbiotics. Probiotics (yogurt, kefir and fermented foods such as kimchi and miso) introduce live bacteria (ferments) that help maintain and improve the balance of the intestinal flora.

Prebiotics are non-digestible substances that promote growth, activity, and a healthy balance of the intestinal flora, without introducing them directly (Gibson and Roberfroid, 1995). Some examples are soluble fibers, such as inulin, which is found in artichokes, cauliflower, asparagus, and Jerusalem artichokes. Other prebiotic sources include bananas, apples, and whole grains, which provide soluble fiber or its fractions with prebiotic activity. Garlic and onions contain fructooligosaccharides (FOS), known for their prebiotic effects.

Postbiotics are metabolic products of probiotic microorganisms and include organic acids, enzymes and peptides, polysaccharides, vitamins, and other bioactive molecules that can modulate immune responses and reduce intestinal inflammation (Salminen et al., 2021). Although postbiotics hold great promise, research in this area is still in its early stages.

Food fortification

Fortification of staple foods can improve nutrition by addressing deficiencies in vitamins, minerals, and antioxidants (Allen et al., 2006). Incorporation of superfoods such as berries, seeds, vegetables, algae, and insects, or individual substances such as vitamins and minerals into common products such as cereals, bread, baked goods, dried fruits, legumes, oils and seasonings, yoghurts, dairy products, as well as specially prepared snacks and bars, can make essential nutrients more accessible and help prevent malnutrition (Calvo et al., 2004). Fortification is particularly beneficial in regions where specific nutrient deficiencies, such as iron and vitamin A, are prevalent, contributing to improved public health outcomes (Ofori et al., 2022). However, fortification must be approached with caution to avoid harmful excesses of certain nutrients. Indeed, while food fortification and consumption of superfoods aim to address nutrient deficiencies, excessive intake of certain nutrients can pose significant health risks.

Excessive intake of vitamin A and related carotenoids, often through fortified foods or supplements, can lead to hypervitaminosis A, a condition associated with symptoms such as nausea, headaches, irritability, and dizziness. More severe effects can include decreased bone mineral density, bone fractures, liver enlargement, and even birth defects. Superfoods like liver and some fortified dairy products rich in vitamin A should be consumed in moderation, particularly by vulnerable populations such as pregnant women and young children (Wrzochal et al., 2019; National Institute of Health, 2022; Orkusz and Dobrzyńska, 2022).

While essential for bone health and immune function, excessive consumption of vitamin D can cause hypercalcemia, leading to kidney damage, cardiovascular issues, and calcification of soft tissues. This is a growing concern as vitamin D is increasingly added to fortified foods and supplements (Vieth, 2006; Vieth, 2007).

Over-fortification of iron in food can result in iron overload, particularly in individuals with genetic conditions. This can lead to liver damage, diabetes, and heart disease. Foods like fortified cereals and red meat should be consumed in moderation to avoid such risks (Liu et al., 2023).

Excessive consumption of omega-3s from supplements or fish oil-enriched foods can lead to increased bleeding risk, immune suppression, and gastrointestinal discomfort. This highlights the importance of balancing omega-3 intake from superfoods like salmon, flaxseeds, and fortified products (Javaid et al., 2024).

Considering all these factors, education on portion sizes, labeling transparency, and dietary guidelines are essential to mitigate the risks of superfood overconsumption and harmful nutrient excesses. Additionally, policymakers and manufacturers should consider population-specific needs when designing fortification programs to avoid unintended health consequences.

Assessment of the sustainability of superfoods

Most nutrients and bioactive molecules can be supplied by both plant-based and animal-based products. However, it is crucial to consider that both options must face environmental and social challenges. On the one hand, large-scale plant production can lead to the overexploitation of agricultural areas, causing negative impacts on biodiversity and soil health, as well as precarious working conditions for workers employed across many supply chains. On the other hand, animal-based products still require enormous land use for feed production and are often associated with intensive farming practices that raise serious concerns regarding environmental sustainability and animal welfare.

Drawing from the extensive scientific literature on the topic (Nelson et al., 2016; Djekic et al., 2014), a shift to plant-based nutrient sources should be considered a more sustainable choice to address global environmental and health challenges. Nevertheless, dietary choices are shaped by a combination of individual, cultural, social, and environmental factors, with affordability remaining a critical choice parameter. Unhealthy dietary patterns are more common among lower socioeconomic groups compared to wealthier ones (Swinburn et al., 2019).

The production of eco-friendly food that is both affordable and nutrient-rich represents a challenge for current agricultural and global food systems (Viroli et al., 2023). Moreover, in many cultures, animal-based foods are deeply embedded in diets, as well as traditional rituals. In this context, food can be viewed as an essential component of cultural evolution, a process that has been significantly accelerated by globalization. Consequently, cultural preferences and culinary traditions, which remain representative of specific regions, are undergoing a major transition influenced by changes in economic, environmental, and social landscapes. In the long term, this transition is going to pave the way for new food habits that reflect the ongoing transformation of society and the environment, striking a balance between sustainability, health, and respect for natural and human resources.

To analyze in more detail the sustainability parameters of superfoods, three products of non-animal origin and three products of animal origin were selected.

Spirulina

Regarding the environmental impact, Spirulina is highly sustainable, even compared to many terrestrial crops, as it requires minimal land and water resources (Amin et al., 2024). It can be grown in controlled environments (open ponds and bioreactors) with water recycling, allowing for good yields with a lower carbon footprint. It requires mixtures of inorganic salts that could be conveniently recovered from co-products collected from other agri-food chains through ultra- and nano-filtration processes.

The cultivation of Spirulina can also contribute to local economies, particularly in regions where traditional agriculture is difficult due to climatic or soil conditions. However, it is essential to scale production sustainably and ensure fair labor practices (Henrikson, 2010).

Goji berries

Goji berries are mainly grown in Asia and require considerable water resources, especially in arid regions where they are often grown. There is also concern about monoculture practices, which can lead to biodiversity loss and soil degradation (Wang et al., 2015).

Global demand for goji berries has led to intensive agriculture, often in economically vulnerable areas (Potterat, 2010). While the market provides income for local farmers, it also raises questions about fair wages, working conditions, and exploitation of local resources.

Quinoa

Quinoa is resilient to harsh climates and has low water needs, making it sustainable for growth in diverse environments (Gómez-Caravaca et al., 2014). However, increased global demand has led to shifts in land use, impacting traditional farming practices and potentially contributing to soil erosion in Peru and Bolivia.

Quinoa production has benefited Andean farmers economically, but rising demand has also led to higher prices, sometimes restricting access for local populations who traditionally relied on it as a staple food (Bazile et al., 2016).

Salmon

Wild salmon populations are at risk from overfishing. On the other hand, salmon farming can have considerable environmental impacts, including water pollution, habitat degradation, and high feed requirements, even though it remains important for boosting local economies, especially in coastal areas (Naylor et al., 2009). In addition, the issues concerning overfishing and environmental degradation are affecting marine ecosystems and local fishing communities (Torrissen et al., 2011).

Fish oil

Fish oil extraction supports economic activity in coastal regions, but sustainability concerns are growing as overfishing disrupts marine food chains, impacting local communities reliant on fish stocks. Overfishing of species like anchovies and sardines has a severe impact on marine resources (Tacon and Metian, 2009). Alternative sources, such as algae-based oils, are being developed to reduce the ecological footprint. Indeed, scientific evidence is collecting promising results about their application as sustainable omega-3 source (Shahidi and Ambigaipalan, 2018).

Beef liver

Beef liver is a nutrient-dense food. However, it comes from beef production, which represents the most impactful animal production in terms of greenhouse gas emissions, deforestation, land use, and water usage (Eshel et al., 2014). Sustainable practices have yet to become widespread in this sector. Such practices must necessarily also include the necessary reduction in the size of animal farming.

Beef liver is one of the least sustainable options due to the high environmental costs associated with beef production, making it a poorer choice compared to other alternatives available in the market (Godfray et al., 2018).

Conclusion

The classification proposed in this article provides a valuable framework for addressing sustainability and animal welfare concerns within the context of global superfood consumption. Organisms that synthesize nutrients, such as plants, algae, and microorganisms offer highly sustainable food options, as they require fewer resources compared to organisms that accumulate nutrients, like animals. Adopting a plant-based superfood diet can help reduce the environmental impact associated with animal production, which leads to high greenhouse gas emissions, water consumption, and land overexploitation. However, it is necessary to practice agriculture in a sustainable way, and with a low environmental impact, preferring crops that can potentially be cultivated at different latitudes and in large areas of the globe, with reduced water and pesticide requirements.

In addition, growing awareness of animal welfare is encouraging consumers to seek more ethical alternatives. The classification proposed in this perspective article emphasizes the potential to meet nutritional needs without relying on animals, favoring the choice of nutrient-rich plant-based foods. This transition to a plant-based superfood diet not only promotes human health but contributes to a fairer and more responsible food system.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GS: Investigation, Validation, Writing–review and editing. GM: Conceptualization, Supervision, Writing–original draft.

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