Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

View Article Online
View Journal | View Issue

Cite this: *Sustainable Food Technol.*, 2026, 4, 2381

Duckweed as a sustainable source: extraction and applications of bioactive nutrients for industrial applications

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Duckweed, a fast-growing aquatic plant belonging to the Lemnaceae family, has been most commonly studied and utilised as a food source due to its excellent palatability and nutrient profile. Other genera, such as *Lemna*, *Spirodela*, and *Landoltia*, are less commonly consumed by humans due to issues like poor palatability. However, they remain of interest for animal feed and bioresource applications. This review synthesises peer-reviewed literature identified through structured searches of major scientific databases, focusing on studies reporting the nutritional composition, extraction technologies, analytical methods, and food-related applications of duckweed species. Therefore, duckweed is recognised as a sustainable, nutrient-rich food source, offering a viable solution to global challenges in food security, environmental sustainability, and nutrition. Across its diverse species, duckweed exhibits considerable variation in macro- and micronutrient composition, including 25–40% protein by dry weight, significant amounts of starch, polyunsaturated fatty acids (PUFAs), essential amino acids, vitamins, and minerals, contributing to its balanced and functional profile as an ingredient for food formulations. Various extraction methods have been employed to isolate bioactive compounds from the duckweed matrix. Advanced techniques, such as enzymatic hydrolysis, microwave-assisted extraction, and ultrasonication, have been applied explicitly to duckweed to facilitate the efficient recovery of high-quality starch, fats, proteins, and bioactive compounds while preserving their functional properties and nutritional value. Additionally, novel analytical methods, including chromatography, mass spectrometry, and proteomic profiling, enhance the understanding of duckweed's species-specific nutrient composition. This review emphasises the nutritional diversity of duckweed and explores innovative technologies for extracting and purifying its active ingredients. Furthermore, it discusses the various industrial applications of duckweed, including functional foods and nutraceutical preparations, and addresses safety and public acceptance challenges. By highlighting the potential of duckweed for developing new food products, this review underscores its role in promoting global food security, alleviating malnutrition, and contributing to sustainable food systems. This area remains a research gap. Given its rapid growth, high nutrient content, and positive ecological impact, duckweed emerges as a critical resource capable of meeting the needs of a growing population.

Received 28th October 2025
Accepted 22nd February 2026

DOI: 10.1039/d5fb00755k

rsc.li/susfoodtech

Sustainability spotlight

Duckweed is a nutrient-dense aquatic plant rich in protein, essential amino acids, vitamins, and minerals, positioning it as a promising superfood for sustainable nutrition. It contains diverse bioactive compounds that confer antioxidant, anti-inflammatory, and antidiabetic properties. Due to its rapid growth rate, minimal land and water requirements, and high biomass yield, duckweed offers a low-impact, renewable solution to global food security challenges. Advanced extraction and processing technologies further enhance nutrient and bioactive compound recovery, enabling their utilisation in functional foods, protein supplements, and nutraceutical applications. This research directly supports the United Nations Sustainable Development Goals 1 (No Poverty), 2 (Zero Hunger), 3 (Good Health and Well-being), and 12 (Responsible Consumption and Production).

1. Introduction

As the global population grows and food security and sustainability become increasingly important, identifying sustainable, nutrient-dense food sources has become a growing focus in

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recent years. Duckweed is an aquatic plant belonging to the Lemnaceae family. It has gained attention as an alternative food source due to its rapid biomass growth rate, high protein content, and versatility under various environmental conditions.[1] Duckweed utilises less land than conventional crops due to its high adaptability under various conditions of water resources,[2] including salinity, temperature, and pH. In addition, duckweed has a high nutritional profile. It contains up to 40% protein and 3% to 75% starch by dry weight,[3] comparable to traditional protein-rich sources like soybeans and legumes. Additionally, duckweed contains high levels of essential amino acids, polyunsaturated fatty acids, vitamins, and minerals, making it a healthy and functional food ingredient.[4] Besides being an excellent source of nutrition, the duckweed plant efficiently takes up nutrients from wastewater during cultivation, offering the dual benefit of water purification and sustainable biomass production, which aligns with sustainable goals for eco-friendly food systems and a circular bioeconomy.[5]

Advancements in extraction and isolation methodologies have further substantiated the potential of duckweed as a commercially viable food ingredient. Recent approaches, such as aqueous extraction, enzymatic hydrolysis, and ultrasonication, have been optimised to recover high-quality proteins, starches, and other bioactive compounds from duckweed while retaining their functional properties.[6] DNA sequencing and metagenomic techniques have facilitated the nutritional profiling of duckweed by integrating advanced methodologies, including high-performance liquid

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chromatography (HPLC), mass spectrometry, and proteomic analysis. These approaches provide a robust framework for accurately determining the nutrient composition of duckweed. Consequently, they underscore the potential of duckweed to address both macronutrient and micronutrient deficiencies in human diets.[7]

Due to its nutritional value, sustainability, and processing potential, duckweed is regarded as a significant solution for addressing global food security challenges. This review aims to provide a comprehensive overview of the suitability of duckweed as a food ingredient and the extraction technologies required to obtain duckweed-derived food ingredients while addressing the food safety issues associated with duckweed production and utilisation. Furthermore, the review will highlight its applicability in food product development and its role in promoting food security and environmental sustainability.

2. Methodology of the review

This review was carried out using a structured literature review and a selective approach to ensure reproducibility and transparency. Peer-reviewed articles were identified from scientific databases, including Web of Science, Scopus, and PubMed, using keywords for duckweed (Lemnaceae), *Wolffia*, nutritional composition, extraction techniques, bioactive compounds, and functional food applications. The search focused mainly on studies published in recent years. Inclusion criteria comprised original research articles and review papers reporting on the nutritional profile, extraction and analytical methodologies, and food, nutraceutical, or bioresource applications of duckweed species. Most studies unrelated to human nutrition, food systems, and the utilisation of bioactive compounds were excluded. Relevant articles were screened based on titles and abstracts, followed by full-text evaluation to ensure alignment with the objectives of the review.

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3. Duckweed species and their potential as a food ingredient

The world population is rapidly growing and is expected to reach 9.7 billion by 2050,[8] necessitating a greater reliance on alternative sustainable food sources to support this expanding population. However, the available natural resources are insufficient to fulfil human needs, given the high demand for healthy, sustainable, and quality foods. Therefore, there is direct pressure on the current food system to find alternative plant food sources for human consumption. Additionally, health implications are arising among consumers due to inadequate nutritional intake, including protein malnutrition. These highlight the urgent need for alternative protein sources.[9] Duckweed produces biomass, a valuable high-protein feedstuff consisting of α-tocopherol and carotenoids. Thus, duckweed protein and processed duckweed products have the potential to become staple offerings in future supermarkets. For example, Asians consume *Wolffioideae*, a duckweed subfamily member, in soup mixes, salads, omelettes, and curry preparations. Most of their amino and fatty acids are beneficial to human health.[10]

Previous studies emphasised duckweed as "eggs of the water" because it was an inexpensive protein source for a few decades, along with species of *Wolffia arrhiza*, which had a high growth rate compared to others.[11] Duckweed exhibits exponential growth as it converts nutrients into edible tissues. The densely populated plant also utilises all nutrients for its development. Duckweed rapidly grows, absorbing 13–38 dry tons per hectare per year, and removing nitrogen, phosphorus, and other nutrients.[12] This high plant yield is attributed to its ability to remove pathogens for industrial applications. In parallel, the removal of mature plants further encourages the growth of younger plants. The availability of ammonium nitrogen (NH_4–N) over nitrate nitrogen (NO_3–N) or nitrite nitrogen (NO_2–N) directly affects high-protein plant materials.[13]

Duckweed could be a valuable protein supplement for people in developing nations, such as Nepal, India, Pakistan, and Bangladesh, where they often consume a high-carbohydrate diet with inadequate protein intake. Duckweed could also serve as a valuable source of protein, enhancing the nutritional value of vegetarian and vegan diets, particularly in developed countries.[14] However, food safety issues should be considered before marketing duckweed as a food for humans. Its safety for consumption needs to be guaranteed, preventing the accumulation of heavy metals such as Zn, Cr, and Cd up to 109.294 mg kg^{-1}, 4.226 mg kg^{-1}, and 0.196 mg kg^{-1} (wet weight),[15] as well as other toxic compounds. Therefore, most countries do not habitually use common duckweed species for human consumption. According to a study, *Lemna minor* and *Wolffia globosa* contain nutritious metabolites that improve the quality of plants as edible food materials and have high fibre content, which supports good digestion in the human body. Additionally, the rich antioxidant content of duckweed helps reduce oxidative stress in the human body.[4] Toxicological studies by Ofoedu *et al.*[16] confirmed that duckweed is safe for human consumption.

Duckweed plants are characterised by their rapid growth, unique plant structure, and ability to utilise nutrients from water resources, while offering valuable nutrition. Typically, duckweed species include the common *Lemna minor*, the swollen duckweed *Lemna gibba*, the giant duckweed *Spirodela punctata*, the rootless duckweeds *Wolffia globosa*, *Wolffia arrhiza*, and *Wolffiella hyaline*. These species contain no roots or only small amounts of roots, which facilitates their ability to absorb nutrients from the water body and absorb a high density of nutrients. This phenomenon significantly contributes to nutrient cycling. Overall, the nutrient composition of duckweed varies among different species.[17,18]

4. Nutritional composition of duckweed

4.1. Macronutrient composition

Duckweed species exhibit an excellent macronutrient composition, making them a valuable resource for human consumption. Protein contents in four duckweed species, including *Spirodela polyrhiza*, *Landoltia punctata*, *Lemna gibba*, and *Wolffia columbiana*, range from 20% to 45% protein, with excellent amino acid profiles. Furthermore, the fat content, including 11 unsaturated and saturated fatty acids, typically ranges from 4% to 7% of the dry weight.[19] Their starch content differs significantly among species, with levels of up to 75% of the dry weight under certain growing conditions, reflecting their potential for energy production.[10]

4.1.1 Starch. The starch content of duckweed can vary under different cultivation conditions, including weather, temperature, relative humidity, and salinity. Salinity increases the starch content in duckweed,[3,20] whereas a lack of phosphate or nitrate and the presence of heavy metals increase the starch content in some duckweed species. Considering starch, *Landoltia punctata* showed a starch content of 72.2% (dry weight basis), 45.68% to 57.23% in *Spirodela polyrhiza* and *Lemna minor*, 26% in *Lemna aequinoctialis* and 24% in *Wolffia arrhizal*.[3,21,22] Typically, amylose and amylopectin are the primary starch components found in plants. Different duckweed species contain varying percentages of amylose and amylopectin, such as 18% and 82% in *L. punctata*, 20% and 83% in *L. aequinoctialis*, and 15% and 87% in *W. arrhizal*. Their amylose and amylopectin ratios were determined to be 0.22, 0.20, 0.18, and 0.15–0.25, respectively.[22,23] Starch availability in duckweed facilitates its utilisation in bioethanol production.[23] The starch structure of duckweed is shown as follows (Fig. 1).

Furthermore, Table 1 compares the properties of duckweed starch with those of other main cereals and root crops.

4.1.2 Protein and amino acids. Sembada & Faizal, and Takács *et al.*[22,35] reported that the protein content of *Spirodela*, *Landoltia*, *Lemna*, *Wolffiella*, *Wolffia*, *L. punctata*, and *W. arrhiza* was 10–37% of the dry weight. Research by Demann *et al.*[42] reported 17% crude protein in *Lemna minuta*, 24.6% in *Lemna minor*, 24.6% in *Spirodela polyrhiza*, and 37% in *Lemna obscura*. The contents of starch and proteins differ with phosphates, nitrates, and other fertiliser applications. Additionally, using a swine medium reduces protein content while increasing starch content.[43] However, it is noteworthy that high nitrate levels and intense light can adversely affect protein production. This means that optimum growth conditions can increase protein content to 40–45% of the dry weight. According to Devlamynck,[44] duckweed species are sustainable protein sources for mitigating protein scarcity and enhancing local nutrient abundance in Europe.

4.1.3 Amino acids. Duckweed encompasses essential and non-essential amino acids, with aspartate and glutamate being the predominant ones. Environmental growth conditions and genetic determinants influence amino acid concentrations.[7] For example, *Wolffia arrhiza* comprises 33.7% essential and 66.3% non-essential amino acids relative to its total amino acid profile. Furthermore, this species exhibits a higher proportion of non-essential amino acids than other species, such as *Landoltia punctata* and *Spirodela polyrhiza*, which contain approximately 50% non-essential amino acids.[43] Notably, the essential amino acid composition of *W. arrhiza* closely aligns with the recommended intakes established by the Food and Agriculture Organisation (FAO), with phenylalanine, threonine, tyrosine, and tryptophan exceeding the FAO recommendations. This suggests that *W. arrhiza* may be a viable source of essential amino acids.[45,46]

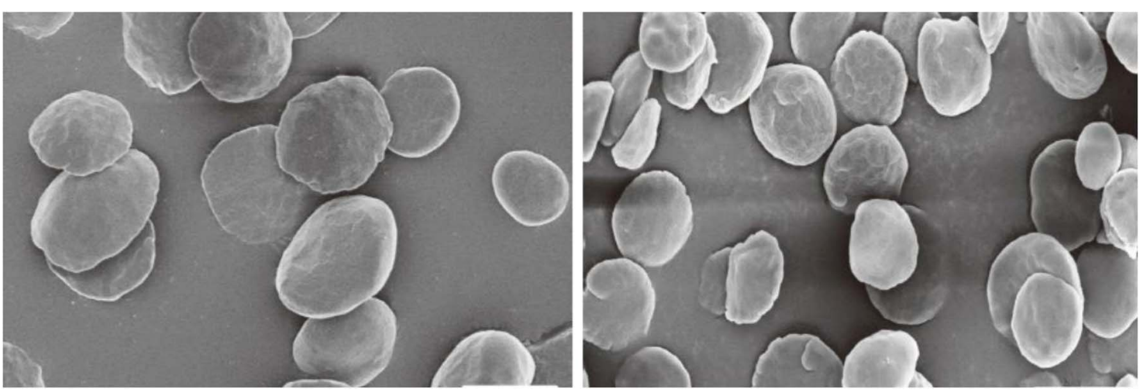

Fig. 1 Structure of the starch granules in duckweed according to the scanning electron microscope view (scale bars = 5 μm), reproduced from Liu *et al.*[23] with permission from the corresponding author Zhou, G., copyright 2020.

Table 1 Properties of duckweed starch compared to other main cereals and root crops

Feature	Duckweed starch	Cereal starch	Tubers/root starch	References
Granule size	Very small (3–8 μm)	Medium (5–50 μm)	Large (15–100 μm, potato can be > 100 μm)	3, 24, and 25
Shape	Mostly spherical/oval	Polygonal (maize), spherical and flattened discoid/oval (wheat), pentagonal/angular (rice)	Oval/round (potato), truncated (cassava)	26–28
Crystalline type	A-type (sometimes A–C mix)	A-type (cereals), B-type (high-amylose maize)	B-type (potato), C-type (cassava and pea)	2, 29, and 30
Amylose content	Moderate (20–38%)	Variable (20–28% in normal maize, <5% in waxy)	Potato ∼30%, cassava ∼22%	31–34
Digestibility	Relatively high due to small granule size and high surface area	Moderate	Lower (*e.g.*, potato resistant starch is higher)	35–37
Gelatinisation temperature	∼65–75 °C	Wheat: 58–64 °C; maize: 62–72 °C	Potato: 58–65 °C; cassava: 56–70 °C	22, 38, and 39
Industrial potential	High (due to rapid digestibility, fine granules, and good film properties) biofuel production, and food additives	Established (bread, noodles, beer, *etc.*)	Established (thickeners, films, and bio-based materials)	10, 40, and 41

The investigation conducted by Kudale *et al.*[47] demonstrated that the species *Wolffia microscopica* and *Wolffia hyalina* have higher concentrations of amino acids critical for human nutrition. Table 2 presents a comparative analysis of these amino acid profiles against common flour sources, including wheat and legumes such as chickpeas, lupins, and peas, which are integral to vegetarian and vegan dietary regimens.

Furthermore, Table 3 compares the properties of duckweed protein with those of other main cereals and root crops.

4.1.4 Fats and fatty acids. While aquatic plants generally exhibit low lipid content, duckweed typically contains a substantial fat content, ranging from 4% to 7% of dry weight. Notably, it is enriched in polyunsaturated fatty acids (PUFAs), particularly omega-3 and omega-6 fatty acids,[16,19,65] which are essential for human health. Among these, alpha-linolenic acid and linoleic acid are predominant and are recognised for their roles in promoting cardiovascular and neurological health. Importantly, species such as *Wolffia microscopica* exhibit a favourable *n*-6/*n*-3 fatty acid ratio, often below 1.0, consistent with dietary guidelines aimed at mitigating the risk of chronic diseases.[22,66]

Compared with total fatty acid (TFA) contents, saturated fatty acids (SFAs) are 25–46%, while palmitic acid represents the most prominent SFA. However, monounsaturated fatty acids are very low, as oleic acid is the prominent one with a maximum value of 11.4% from the total fat in *L. minor*.[67] In addition, a study by Apperonth *et al.*[49] showed that the content of polyunsaturated fatty acids (PUFAs) is very high in *L. punctata* (48%) and *W. microscopica* (71%). Additionally, the PUFA content accounts for more than half of the total fatty acids. A few authors, including Baek *et al.* and Yan *et al.*[2,68] have studied all species that exhibit higher *n*-3 fatty acids than *n*-6 fatty acids, possibly due to a high α-linolenic acid content and a low γ-linolenic acid content. However, stearidonic acid has been detected at minor levels in *L. gibba*, *W. microscopica*, and *L. minor*.[69] Furthermore, the proportion of fatty acids *n*6/*n*3 ratio was less than 0.3 in three duckweed species, including *L. gibba*, *S. polyrhiza*, and *W. hyaline*, whereas it was 0.5 in *L. punctata* and *L. minor*.[70] Duckweed exhibits a higher content of saturated fatty acids (SFAs) and a lower proportion of monounsaturated fatty acids (MUFAs) than most other plant oils, except for coconut and palm oils. Notably, it is characterised by significant levels of

Table 2 Amino acid contents of duckweed species (values are expressed as g/100 g protein)[a]

Amino acid	His	Ile	Leu	Lys	Met	Phe	Trp	Thr	Val	References
L. gibba	1.6–1.9	3.4–3.9	7.1–7.2	4.1–4.2	1.2–1.6	4.3–6.6	0–0.9	3.2–4.8	2.2–4.5	48, and 49
S. polyhiza	1.6–2.2	3.3–3.9	6.8–6.9	4.2–4.3	0.8–1.6	4.20	NA	3.5–4.2	0.8–4.4	50
L. puncata	1.4–1.9	3.8–5.2	6.8–6.9	4.3–5.9	1.1–2.0	4.4–4.9	NA	3.3–4.3	4.7–5.4	22
W. arrhiza	1.1–1.6	2.7–4.9	5.4–6.8	4.1–5.5	0–2.1	0–4.6	NA	2.8–3.6	3.3–5.2 2	45, and 50
FAO	1.90	4.20	4.80	4.20	2.20	2.80	1.40	2.80	0.90	51
Wheat	1.5–2.3	3.1–4.1	4.9–6.8	2.0–3.1	0.8–1.5	3.3–5.3	0–1.30	2.4–3.4	3.5–4.9	52
Chickpea	2.9–3.2	4.5–4.8	8.1–8.5	6.7–7.0	0.8–1.1	5.0–5.3	0.8–0.9	2.7–3.0	4.1–4.6	53
Lentil	0.9–2.5	1.2–3.8	2.1–7.8	1.9–7.3	0.3–0.8	1.4–4.5	0.2–1.2	1.1–3.0	1.4–4.5	53
Soy	2.3–2.5	0–3.7	7.5–9.2	6.3–6.6	1.2–1.3	4.9–5.7	0–1.3	3.6–3.9	3.9–5.0	51

[a] NA – not applicable.

Table 3 Properties of duckweed proteins compared to other main cereals and root crops

Aspect	Duckweed proteins	Cereal proteins	Legume proteins	References
Major fraction	RuBisCO (soluble)	Storage proteins (prolamins and glutelins – often insoluble)	Globulins (salt-soluble)	54, and 55
Digestibility	High (80–90% true digestibility)	Variable: wheat gluten lower digestibility	Generally high	18, 56, and 57
Essential amino acids	Rich in lysine (better than cereals) and moderate methionine	Limiting lysine	Limiting in methionine	51, 58, and 59
Structural form	Mostly globular and soluble proteins	Many insoluble and aggregated proteins	Mostly globulins (11S) and albumins (7S)	54, 60, and 61
Applications	Functional foods, protein supplements, and feed	Bread, pasta, and brewing	Protein isolates, concentrates, and texturised proteins	62–64

polyunsaturated fatty acids (PUFAs), including linoleic acid and gamma-linolenic acid (n-6), as well as α-linolenic acid and stearidonic acid (n-3).[71] *W. microscopica* consists of 71% high and *W. globosa* contains a low proportion of polyunsaturated fatty acids (PUFAs) at 54%,[69] followed by other species such as *Lemna minor* (21–37%)[72,73] and *Wolffia hyalina* (63%).[69] Omega-6 fatty acids are abundant in *W. microscopica*, accounting for 26.77% of its total fatty acid content, which is beneficial to human health. *W. microscopica* contains 25.07% saturated fatty acids (SFAs) compared to 39.85% in *S. polyrhiza* and 46.23% in *L. punctata*. However, the MUFA content of these species ranged from 4.13% to 5.23%.[22,69]

4.2. Micronutrient composition

4.2.1 Vitamins. Duckweed is typically rich in fat-soluble vitamins, including vitamin A (in the form of carotenoids), vitamin E (tocopherols), and vitamin K. Notably, it contains abundant carotenoids such as lutein, beta-carotene, zeaxanthin, and violaxanthin, which are significant contributors to its antioxidant properties.[74,75] Tocopherols, the precursors of vitamin E, enhance antioxidant capacity, mitigate lipid oxidation, and promote cellular health. Additionally, duckweed is a substantial source of water-soluble vitamins, mainly vitamin B12 (cobalamin), which is essential for nerve function and energy metabolism. Its high folate (B9) content is particularly beneficial for DNA synthesis, helping to prevent folate deficiency in pregnant women. Consequently, duckweed presents considerable potential as a functional food ingredient and a sustainable source of essential vitamins to address global nutritional challenges.[74,76]

4.2.2 Minerals. The investigation conducted by Hu *et al.*[45] quantified the macro- and trace-mineral content of *Wolffia arrhiza*, revealing that macro-mineral concentrations ranged from 1.64 to 34.86 g per kg dry weight, with sodium exhibiting the lowest concentration and potassium the highest. Calcium, phosphorus, and magnesium were also quantified at 8.55 g kg^{-1}, 13.81 g kg^{-1}, and 2.55 g kg^{-1}, respectively. Trace mineral concentrations varied from 6.33 to 431.2 mg kg^{-1}. These discrepancies may be attributed to the nutrient medium and the specific plant species.[45,71] These minerals play a crucial role in human bone health and regulate oxidative stress within the body. Notably, the macro- and microelement profiles of both *W. arrhiza* and *W. microscopica* were comparable, indicating that the composition of the culture medium influences these mineral contents.[69]

5. Functional properties of duckweed

Duckweed can potentially mitigate various chronic diseases due to its rich bioactive compound profile, including essential minerals, beta-carotene, lutein-like phytochemicals, and vitamins.[62,77] Additionally, glycosylated flavonoids are prevalent in duckweed species. Research has identified distinct flavonoids across various duckweed species that may exert beneficial effects (Table 4) in managing diabetes, inflammatory conditions, hepatic disorders, and mutagenic activities within the human body.[78,79] Furthermore, when ingested, these flavonoids are readily absorbed in the small intestine, demonstrating the characteristics of an exemplary functional supplement.[80] Notably, *Landoltia punctata* has been found to contain significant levels of apigenin, which exhibits promising anticancer properties.[14]

Duckweed is also a source of diverse polyphenolic compounds that have been shown to reduce intrahepatic fat accumulation.[88] *Wolffia arrhiza* exhibits a higher total phenolic content (TPC) of 7.57 ± 0.04 mg per g dry weight compared to several medicinal plants, such as cinnamon and various cereal grains (0.69–2.71 mg per g dry weight).[18] The TPC of *Lemna gibba* was reported to be 3 mg per g fresh weight. However, the phenolic content in duckweed is approximately 3 to 10 times lower than that found in berry species, despite the abundance of flavonoids in species such as *L. punctata* and *Wolffia globosa*.[18,89]

Although certain duckweed species are considered valuable sources of flavonoids, limited research has been conducted to quantify these compounds.[90] For instance, *W. arrhiza* contains 1.42 ± 0.03 mg per g fresh weight, surpassing the flavonoid content of several edible vegetables and fruits, including berries (0.19–1.27 mg per g fresh weight).[91] Consequently, the phenolic compounds in duckweed may contribute to various physiological functions, including antibacterial, antioxidant, and anti-

Table 4 Evidence-based health effects of duckweed across experimental models

Health benefits	*In vitro* evidence	Animal study evidence	Human study evidence
Antioxidant effects	Antioxidant and radical scavenging activities[77] Significant inhibition of lipid peroxidation activities in duckweed extracts[83]	Supplemented feed for dairy cows to enhance antioxidant activity and hematologic effects[81]	Pharmaceutical application of *Lemna minor* for rheumatism, allergies, asthma, vitiligo, jaundice, and glaucoma[82]
Antidiabetic effects	Bioactive compounds like phenolics and flavonoids exhibit antidiabetic activities[79]	No explicit animal studies	*Wolffia globosa* shows a lower postprandial glucose peak and faster return to baseline glucose levels compared to a yogurt shake[84] *Lemna minor* consumption resulted in lower plasma glucose and insulin levels compared with peas[85]
Anticancer potential	Antileukemia agents from duckweed (Liu, 2024)[23]	No explicit animal studies	No explicit human trials
Immune-enhancing effects	Immunological effects of duckweed species compared to other plant and animal foods[16]	Duckweed-based vaccine targeting avian infectious bronchitis virus (IBV), a highly contagious respiratory pathogen in poultry[86] Duckweed (*Spirodela polyrhiza*) based commercial feed on grass carp[87]	No explicit human trials

inflammatory activities.[89] Thus, *W. arrhiza* is significant as a nutritious and edible species. According to Muller *et al.* and Gulcin*et al.*[18,83] the antioxidant activity of *W. arrhiza*, as measured by 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), and ferric reducing antioxidant power (FRAP) assays, was found to be superior to that of cereals, yet lower than that of fruits and vegetables, highlighting its phenolic and flavonoid content as key contributors to its antioxidant efficacy compared to commonly consumed fruits and grains, such as maize, soya and cinnamomum species.

6. Available bioactive compounds

Wolffia is a notably nutritious species rich in bioactive compounds, such as phytosterols and carotenoids, which contribute to the development of functional foods and nutraceutical preparations (Table 5).

Among these phytosterols, the most abundant type is β-sitosterol (57–84%), which offers cholesterol-lowering and anti-inflammatory properties to the human body,[72] followed by campesterol (5–11%) and stigmasterol (1–20%); these compounds further enhance its cardiovascular and anti-inflammatory activities.[95] Small amounts of Δ5-avenasterol (2–9%) are beneficial to antioxidant activity\`. Considering carotenoids, *Wolffia* species contain high amounts of (all-*E*)-lutein (41–79%), which improves eye health, alongside (all-*E*)-beta-carotene (11–33%), which serves as a precursor to vitamin A and an antioxidant. In addition, both tocopherols are potent in terms of vitamin E activity; all these compounds are beneficial in managing oxidative stress, cardiovascular diseases, and vision-related disorders.[96,97] In addition to these compounds, phenolics of chlorogenic acid (*S. polyrhiza*) derivatives and flavonoids are available in duckweed species. For instance, apigenin (*L. punctata*), luteolin (*Wolffioideae* s), chrysin, nobiletin, tangeretin, wogonin, and baicalin are exceptionally prominent for their antioxidant and anticancer potential. *S. polyrhiza* contains secondary metabolites such as orientin and vitexin.[79] Apigenin derivatives such as 5-*O*-(*E*)-caffeoylquinic acid, 3-*O*-(*E*)-cou maroylquinic acid, luteolin-7-*O*-glucoside-*C*-glucoside, 4-*O*-(*E*)-coumaroylquinic acid, luteolin-6-*C*-glucoside-8-*C* rhamnoside, and luteolin-8-*C*-glucoside-6-*C*-rhamnoside have been described in a study.[79,98]

7. Extraction and isolation techniques of bioactives

The extraction and isolation of various components from duckweed are achieved using several advanced techniques to

Table 5 Phytosterols and carotenoid compositions of *Wolffia* species

Phytosterols type	Available percentage	Carotenoid type	Available percentage	References
Beta-sitosterol	57–84%	(All-*E*)-lutein	41–79%	69, and 92
Stigmasterol	1–20%	(All-*E*)-beta-carotene	11–33%	69, 92, and 93
Δ5-Avenasterol	2–9%	(9*Z*)-Beta-carotene	2–7%	69, and 94
Campesterol	5–11%	(All-*E*)-zeaxanthin	1–3%	69
Phytol	3–5%	Alpha-tocopherol	2–13%	69

recover proteins, lipids, phytosterols, carotenoids, and vitamins, while preserving their bioactive properties. Solvent extraction employing non-polar and polar solvents, such as hexane or ethanol, is practised for polyphenols, carotenoids, and lipids. In contrast, green technologies utilise lipophilic compound extraction without solvents.[99] Ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) increase cell rupture efficiency, while heating (direct ultrasonication, microwave heating, and joule heating) increases the levels of phenolics, proteins, and pigments. Furthermore, enzymatic hydrolysis using cellulase or protease is suitable for releasing proteins and polysaccharides.[100,101] Purification of specific compounds can be carried out using high-performance liquid chromatography (HPLC) and gas chromatography (GC), such as fatty acids, phenolics, alkaloids, and phytosterols.[102,103] These techniques, designed to harness the specific properties of duckweed compounds, confirm the capability of duckweed for functional food, nutraceutical, pharmaceutical, and bioenergy applications.[35,104] Still, few studies have been carried out to describe the extraction and isolation of duckweed ingredients.

7.1. Protein extraction methods

Different methods are used to extract proteins, categorised as conventional and advanced. Solvent extraction, mechanical breakdown, and heat- and salt-induced precipitation are conventional methods for efficiently and cost-effectively extracting proteins. However, their challenge lies in maintaining the stability and purity of the protein.[105,106] However, ultrafiltration, enzymatic hydrolysis, ultrasound-assisted extraction, microwave-assisted extraction, liquid extraction, supercritical extraction, and dialysis-like methods facilitate the purification of proteins.[41,107] Therefore, careful selection of the extraction method is crucial, depending on the specific research purposes. As mentioned by Nitiwuttithorn *et al.* and Justino *et al.*,[101,108] techno-functional properties can vary with the extraction method, as confirmed by using conventional, alkaline, and ultrasonic methods. Moreover, the ultrasonication method is considered the most effective method for extracting protein,[109] with a higher yield of 80.83%.[110]

For protein extraction, samples are used after lipid extraction to avoid interference with protein release.[111] Furthermore, adjusting the pH in solutions would facilitate extraction processes. Regarding solvents, aqueous extraction (for water-soluble proteins) and alkaline extraction (to improve solubility) are important considerations when applying enzymatic hydrolysis for cell wall degradation. Soybean, microalgae, and duckweed proteins can be utilised through aqueous extraction, using enzymes such as cellulase and pectinase to break down the cell wall matrix and dissolve water-soluble proteins.[112,113] Research by Muller *et al.*[18] suggested that duckweed protein extraction and solubilisation can be maximised with response surface methodology.

In alkaline extraction, sodium hydroxide is used to solubilise proteins from rice, legumes, wheat, and oilseeds. For the plant matrix, alkaline pretreatment can interfere with lignin and hemicellulose.[114] However, treatment with cellulase and xylanase-like enzymes can remove these contents. Therefore, combined methods can improve extraction efficiency.[115]

7.2. Fat extraction and purification

Under conventional methods, solvent-based extraction and Soxhlet extraction can effectively isolate crude lipids with the aid of centrifugation (Fig. 2).[116] Furthermore, simple filtration and rotary evaporation are beneficial for getting the required extracts. Hexane, petroleum ether, and diethyl ether-like solvents are commonly used media to extract crude fats.[117,118] These traditional methods do not yield pure compounds, raising concerns about environmental and safety impacts. The

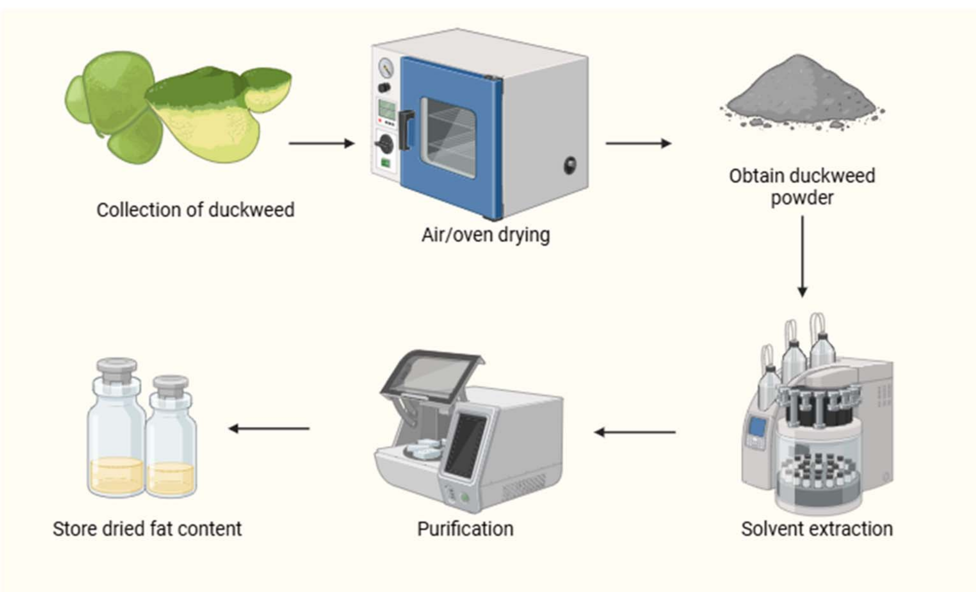

Fig. 2 Basic steps of solvent extraction of duckweed fat.

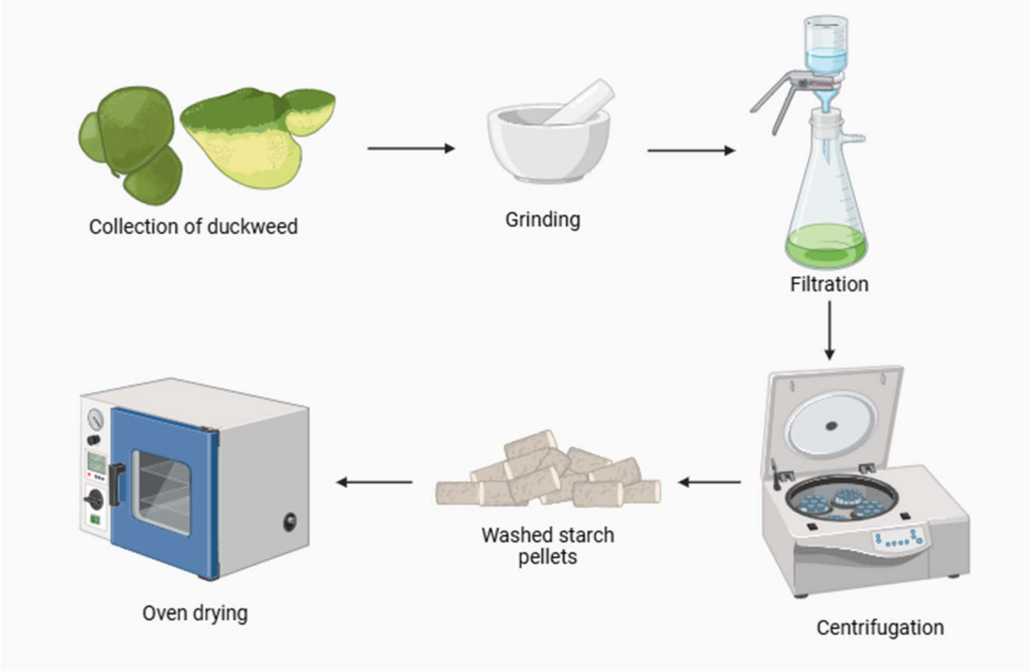

Fig. 3 Basic steps to extract duckweed starch.

maceration method is suitable for fat extraction.[119] Advanced techniques, such as supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and enzymatic methods, improve lipid yield and purity while also reducing environmental impact. The principle of these methods involves breaking down cells through innovative approaches, such as ultrasonic waves, microwaves, or enzymes, which release lipids into specific solvents. After these extractions, purification steps are essential to separate the pure compounds using centrifugation, chromatography, deacidification, and winterisation, thereby improving efficiency and sustainability.[120,121]

According to the solvent used, the extracted lipid components differ. Polar solvents (ethanol and methanol) and non-polar solvents (chloroform, ether, and hexane) offer different recovery options. Sterols, fatty acids, and triglycerides mainly represent the lipid fraction.[122,123]

7.3. Starch extraction

Typically, the starch content of duckweed ranges from 3% to 75.9% of its dry weight. In the starch extraction process, breaking the cell wall matrix helps release starch granules, separating them from non-starch components. Conventional methods, such as mechanical disruption (Fig. 3), wet milling, and water and alkaline extraction, are cost-effective and widely applicable.[22,124] However, these result in lower purity due to the co-extraction of proteins and fibres with starch.[125] Therefore, advanced techniques such as enzymatic hydrolysis, ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE) can enhance starch yield and purity by effectively breaking down the cell walls. In addition, these methods reduce the required time and environmental impact but require higher costs and technical knowledge for handling. For starch purification, washing, centrifugation, and filtration techniques have been employed to remove impurities, primarily proteins and fibres, before the extracted starch is used for further applications. This is because starch is often modified for both food and pharmaceutical use, as well as for the development of biopolymer materials.[126,127]

In addition to these active compounds, polyphenols and bioactive substances can be produced through conventional and advanced methods, depending on the requirements of the solvents and extraction conditions, which may vary.[128,129]

8. Applications of duckweed across various fields

According to previous researchers, duckweed has a wide range of applications in various fields, as shown in Table 6.

9. Applications in the food industry

Duckweed, recognised for its rapid growth and adaptability as an aquatic plant, possesses attributes that make it suitable for various industrial applications, particularly in the food sector. Key characteristics include its high protein content, essential amino acids, beneficial fatty acids, starch, and bioactive compounds. These attributes position duckweed as a nutritionally versatile raw material for food formulation and preparation. Consequently, its potential applications are increasingly being explored for the development of functional foods and nutraceutical products, emphasising its role as a sustainable and health-promoting ingredient.[6,16]

Table 6 Duckweed applications relevant to different fields

Area/field of application	Research findings and proposed applications	References
Human nutrition source	High amounts of protein, vitamins and minerals and a good source for reducing malnutrition issues	16, and 62
Functional foods and nutraceuticals	Utilisation of bioactive ingredients for product development using duckweed powder and extraction of pure compounds for nutraceuticals	130, and 131
Production of animal feed	Good feed for poultry, livestock, and aquaculture due to its high protein content. Furthermore, its high digestibility makes it a good source of nutrients. Duckweed minerals and bioactives also serve as feedstuff, *e.g.*, improving physiological conditions (hematologic and antioxidants) in the dairy cow	42, and 132
Pharmaceutical applications	Comprising bioactive ingredients that have antioxidant, anti-inflammatory, and antimicrobial properties	133, and 134
Cosmetics	Bioactive ingredients and moisturising abilities facilitate skincare product development	82, and 135
Bioenergy production	High starch content facilitates bioethanol and biogas production	136, and 137
Fertiliser applications	High nutrient content enables the use of duckweed as an organic fertiliser	138, and 139
Phytoremediation/wastewater treatments	The ability to direct the absorption of heavy metals and nutrients from wastewater would reduce environmental pollution E.g.: reduction of cadmium accumulation issues	5, and 140
Bioplastics production	Biodegradable plastics can be produced with the high-starch raw material	141, and 142

Moreover, incorporating duckweed into food systems enhances nutritional profiles and contributes to environmental sustainability by providing efficient biomass production with minimal resource input. Its ability to thrive in diverse aquatic environments allows for the use of non-arable land and wastewater, thereby reducing the ecological footprint associated with traditional agricultural practices. As research continues to elucidate the health benefits and functional properties of duckweed-derived products, their integration into modern dietary regimens is poised to address nutritional deficiencies and meet the growing demand for sustainable food sources.[62,143]

9.1. Functional food development

The nutrient-dense profile of duckweed, encompassing proteins, amino acids, dietary fibres, polyunsaturated fatty acids (PUFAs), and bioactive polyphenols, positions it as an ideal candidate for functional food formulations. The high-quality proteins found in duckweed offer significant advantages over traditional animal proteins, making them suitable for use as plant-based meat alternatives.[22,130] Additionally, these properties facilitate the development of protein-enriched beverages and dietary supplements.

Duckweed's bioactive compounds, including carotenoids, phenolics, and phytosterols, can be integrated into conventional food production systems to enhance antioxidant and anti-inflammatory effects. This versatility allows for the creation of functional snacks, soups, biscuits, and fortified cereals. Furthermore, Muller *et al.*[18] noted that starches derived from duckweed can be utilised in gluten-free products and as thickening agents in sauces and desserts. Moreover, extracting protein isolates, hydrolysates, and peptides from duckweed can significantly improve the functional properties of food preparations, including emulsification, thickening, solubility, and antimicrobial activity. These attributes underscore the potential of duckweed as a valuable ingredient in the development of innovative, health-promoting food products.[62] As mentioned by Akyüz (2025),[144] duckweed protein concentrate can enhance the sensory properties of bakery and snack products by improving the texture properties of snack bars, roll breads, and muffins with significant consumer acceptance. The study by Rahman *et al.*[145] showed that sensory evaluation of duckweed crackers confirms that 6% duckweed powder-containing crackers are acceptable for taste and texture, while overall acceptability is higher with the 2% formulation, which may be due to the reduced green colour being most preferred by participants. Furthermore, more studies are needed to understand how food processing (milling, fermentation, cooking, *etc.*) and preparation methods affect the nutritional value and bioavailability of duckweed components.[35]

Due to their high availability of essential amino acids, duckweed species exhibit superior digestibility and amino acid profiles compared to certain grain species, such as soy and mung beans. Consequently, duckweed powder is an effective protein supplement for athletes, older adults, vegetarians, and vegans. Additionally, its rich mineral content makes it a valuable source of micronutrients, including calcium, iron, and vitamin B.[19,48] Thus, incorporating duckweed can play a significant role in addressing protein malnutrition.

Beyond direct consumption, duckweed powder can be incorporated into baked goods and ready-to-eat meals, enhancing both flavour and functional properties. Furthermore, proteins derived from duckweed can enhance the emulsifying, water-holding, and gelling properties of plant-based meat alternatives, offering a vegetarian and vegan option.[5,42] As a fibre-rich source, duckweed also supports gastrointestinal health. Additionally, duckweed powders can be utilised to formulate immune-boosting and antidiabetic beverages.[146] These attributes underscore the potential of duckweed as a versatile ingredient in health-oriented food products.

9.2. Nutraceuticals

As nutraceutical ingredients, the bioactive compounds in duckweed, including phenolics, phytosterols, tannins, omega-3 fatty acids, and carotenoids, confer significant antioxidant, anti-inflammatory, and cholesterol-lowering effects, thereby supporting cardiovascular health, immune function, and cognitive well-being.[19,147] Extracted polysaccharides serve as effective prebiotics, promoting gut health, while the high concentration of phytosterols helps reduce LDL cholesterol levels. Polyunsaturated fatty acids (PUFAs), particularly omega-3 fatty acids, position duckweed as a beneficial supplement for heart and brain health.[148,149]

Encapsulated forms of these bioactive compounds, whether in powder or liquid form, are well-suited for integration into the nutraceutical market, as they align with the growing consumer demand for sustainable, functional food products. This potential for incorporation underscores the relevance of duckweed as a valuable source of health-promoting ingredients in contemporary dietary regimens.

10. Challenges in duckweed cultivation and utilisation

10.1. Food safety and regulatory issues

The consumption of duckweed as a food source for humans and animals raises concerns about its safety, necessitating thorough scientific investigation. Studies indicate that, as an aquatic plant, duckweed may be susceptible to microbial contamination by pathogens such as *Escherichia coli*, *Salmonella* species, parasites, and various viruses.[150,151] Additionally, duckweed contains heavy metals. Normally, FAO/WHO standards set a maximum level of cadmium (Cd), lead (Pb), nickel (Ni), iron (Fe), copper (Cu), zinc (Zn) and arsenic (As) at 0.2, 0.3, 67.9, 425.5, 73.3, 99.4 and 0.1 mg kg^{-1} (wet weight).[152] However some species such as *Lemna minor* and *Lemna gibba* duckweed contain Cd, Pb, Ni, and Cu at levels of 0.6–0.8, 13.9–20.0, 2.46, and 12.2 mg kg^{-1} (wet weight) where Cd and Pb exceed the recommended levels,[153] and these values may vary depending on the level of pollution in the water body or growing environment, as duckweed efficiently absorbs and accumulates heavy metals from wastewater. In addition to cadmium, lead, and arsenic, duckweed can also accumulate other metals, such as chromium (Cr) and mercury (Hg), as well as pesticides and other toxicants, through the uptake of contaminants from contaminated water sources.[154]

Research conducted on duckweed species revealed that heavy metal concentrations were within acceptable safety limits.[155] However, certain antinutritional compounds, such as tannins, phytates, and protease inhibitors are also present. Considering these antinutrients, phytate levels above 5–6 mg g^{-1} and oxalates above 0. 25 mg g^{-1} can impair mineral absorption. While oxalates play a role in metal tolerance and detoxification, they can also hinder the absorption of key nutrients, particularly calcium and magnesium.[35,156] As mentioned by Chaji and Pormhammad[157] total tannin, dense tannin, phytate, and saponin contents of *Lemna gibba* are 20.2, 0.2, 25.0, and 0.40 g per kg dry weight, which affect the antinutrient activity in human and animal bodies. Although duckweed contains phytic acid in lower quantities than other plant-based foods, its impact on the bioavailability of amino acids and minerals has been minimal, with no significant cytotoxic effects observed in developing cells.[158]

Furthermore, when harvested from unmanaged ecosystems, duckweed may be contaminated with harmful algal blooms that can produce toxins.[159] The polyphenolic compound tannin can inhibit gastrointestinal bacteria responsible for the absorption of certain minerals and vitamins.[160] While duckweed contains higher levels of these compounds than some cereals, their overall effect on amino acid absorption is relatively minor.[4] Thus, while duckweed presents nutritional benefits, careful consideration of safety and potential contaminants is essential for its use as a food source.

10.2. Suggestions for overcoming safety issues and enhancing utilisation

To mitigate the risks of heavy metal accumulation in duckweed, it is essential to implement stringent water-quality management practices to ensure the safety of these species for human consumption. When duckweed is prepared for food or dietary supplements, the Food and Agriculture Organization (FAO), Codex Alimentarius, and regional food safety authorities must establish guidelines for cultivation, processing, and labelling. Before entering commercial markets, relevant organisations should conduct comprehensive risk assessments.[5,161]

Additionally, researchers focusing on duckweed should further investigate its nutritional composition, toxicological properties, and clinical applications. Environmental authorities can play a crucial role by issuing certifications to duckweed cultivators who adhere to sustainable agricultural practices. This multifaceted approach will enhance the safety and viability of duckweed as a food source while promoting responsible cultivation methods.[135]

Utilising preservation techniques during duckweed powder production helps retain its nutritional value while minimising contamination. To improve duckweed production, seeds can also be produced through cross-fertilisation while undergoing genetic modifications.[23,162]

11. Conclusion and needed future studies

Duckweed, recognised as a sustainable and nutrient-rich food source, offers a viable solution to meet the nutritional needs of a growing global population. Its nutrient-dense profile supports extraction and isolation processes that enhance the bioavailability of these nutrients while preserving the plant's inherent properties. The nutritional composition of duckweed suggests its potential as a dietary supplement and a functional food ingredient, thereby enhancing the value of existing commercial food products.

Further research into the health benefits of duckweed-based ingredients is essential to establish their significance in the food sector and among consumers. Duckweed could play a pivotal role in promoting food security and healthy dietary choices by leveraging its sustainability and nutritional benefits. It represents a promising alternative to traditional food sources, positioning itself at the forefront of sustainable nutrition.

To ensure the continued viability of duckweed as a sustainable food source, it is crucial to optimise cultivation practices that minimise environmental impact, advance extraction methods for bioactive compounds, and enhance nutrient bioavailability. Additionally, consumer acceptance can be bolstered through comprehensive safety and risk assessments of extracted and isolated components before their application in functional foods and nutraceuticals.

Author contributions

M. W.: outlining and writing the original manuscript draft. R. H.: drafting the manuscript. R. L.: supervision, writing and reviewing the manuscript. S. W.: supervising the writing. R. R. B.: idea generation, supervision, reviewing and editing of the manuscript throughout the writing process. All authors read and approved the final manuscript.

Conflicts of interest

No competing interests.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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