European Journal of Nutrition & Food Safety

Volume 16, Issue 7, Page 87-104, 2024; Article no.EJNFS.117327
ISSN: 2347-5641

Advances in Algal Biotechnology: Sustainable Production of Nutrient-Rich Biomass and High-Value Bioproducts

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ejnfs/2024/v16i71458

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/117327

Received: 01/04/2024
Accepted: 04/06/2024
Published: 14/06/2024

Review Article

ABSTRACT

Microalgae (MiA) have been portrayed as a sustainable alternative for conventional sources of biofuels, several food and feed systems, and renewable energy sources. Microalgal biomass has attracted considerable attention for its potential to produce high quantities of value-added compounds, including pigments, vitamins, polyunsaturated fatty acids (PUFAs), and antioxidants. In this context, a plethora of existing and potential studies and reviews elicit the applied technologies for bio valorization of algal biomass and sustainable and integrated biorefinery approaches for production of high-value products. The focus of the present review is to provide insights on current trends in the production of lipids and pigments from the alga biomass, and employing eco-conscious methodologies for the extraction of compounds from the microalgal biosphere holds significant importance.

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Cite as: *Singh, Aditi, Surendra Nath Pandey, Khushbu, and Harsh Kumar. 2024. "Advances in Algal Biotechnology: Sustainable Production of Nutrient-Rich Biomass and High-Value Bioproducts". European Journal of Nutrition & Food Safety 16 (7):87-104. https://doi.org/10.9734/ejnfs/2024/v16i71458.*

Keywords: Microalgae; functional lipids; vitamins; bioactive phenolic compounds; extraction; algal biomass; utilization.

1. INTRODUCTION

Current trends of data available on the per capita availability of food resources directs towards a scarcity of production both as food stock and feedstock i.e., the current food production capacity and potential is not completely sustainable to contain and fulfill the enormous increment in requirement of food (25% - 70%) [1] relative to the rising population, expected to be at 9.7 billion by 2050, neither quantitatively nor qualitatively. Alternatively, new evidences portray that approximately 690 million people (8.9% globally) were found to be suffering with nutrient deficiency in 2019, with the figure expected to rise to 840 million by 2030. Asia, Latin America, Africa, countries of the Caribbean region are the most affected [2]. Thus, there is a requirement of novel sources of food which are adequate in terms of amount, nutritional profile, sustainability, and compatibility with the existing resources. [3], [4,5]. There is a tremendous diversity of micro-algae (MA) species, with a high occurrence in the marine systems, fistramenopiles such as Chaetoceros muelleri, and Thalassiosira pseudonana [6] and dinophyta such as Crypthec [7] are dominant in marine systems.

Most of the organisms belonging to the algal constitution are aquatic and photosynthetic in nature, but a few are terrestrial [8]. Approximately for producing 1 kg algal biomass rich in high-quality lipids, digestible proteins and bioactive compounds 1.83 kg of CO_2 is required [9]. Utilizing biorefinery approach wherein the waste streams can be utilized as nutrients source to produce microalgal biomass single algal specie can be cultivated for valorization, as 90% of algal biomass can be valorized into food, feed, energy, or compounds with high value as opposed to higher plants. [10], [11]. Algae biomass is commercially utilized in human nutrition, nutraceuticals, pigments, biofuels, animal feed, cosmetics, and bio-fertilizers [12]. Algae and cyanobacteria pose versatile advantages which deem them suitable for aforementioned applications. Firstly, water serves the purpose of electron donor for oxygenic photosynthesis [13] also, the present an inordinate biomass productivity/ acre in comparison to oilseed crops and such yield is not achievable using current agricultural systems [14], Moreover, they are a nonfood feedstock thus are resolution for food vs feed resources [15]. Their culture is rapid and doesn’t require agriculture land [16], they are efficient adaptors of growth conditions such as seawater, brackish water, and wastewater [17]. Finally, they can be utilized to formulate a diverse array of products of sustainable nature [18,19].

Microalgal biomass has been portrayed as a sustainable alternative for conventional sources of biofuels, several food and feed systems [20]. One of the secondary advantages of incorporating the usage of microalgal technology in the industry is the potential of algae to trap CO_2 round the application and biomass production processes, hence reducing CO_2 emissions and carbon footprint [21].

The industrial application requires cultivation at a mass level which encounters the cost constraint in comparison to the raw materials of other origin for similar purposes [22]. Enhancing cost-effectiveness and economic feasibility of utilizing MiA biomass can be accomplished through various avenues such as optimizing the efficiency of bioreactors, Utilizing cost-effective nutrient sources, namely domestic and industrial wastewater, can significantly contribute to reducing expenses and enhancing the economic viability of MiA biomass utilization. And lastly, enhancing the completeness of extraction of target compounds from the biomass [23]. The fundamental processes for recovering microalgae from their growth medium encompass bulk harvesting, co-cultures with bacteria, fungi, or multiple strains, gravity sedimentation, filtration, and concentration stages. Advances in coculture algae-flocculation are facilitating the production of natural bioproducts with potential applications in fuel and food additives. Additionally, genetic tools and resources are being developed to enhance harvesting efficiency and the creation of novel bioproducts [24].

In this context, a plethora of existing and potential studies and reviews elicit the applied technologies for bio valorization of algal biomass. The focus of the present review is to provide insights on current trends in the valorization of algal biomass and sustainable and integrated biorefinery approaches for production of high-value products. Also, a framework for the use of algae as a possible origin of bio-products rich in nutrients, natural reservoir for valuable biochemicals, including proteins with high biological value and availability, bioactive peptides, minerals, polysaccharides, vitamins, dietary fibre, functional lipids, fatty acids (FAs), pigments etc.

2. NUTRITIONAL COMPOSITION OF ALGAE

The abundantly available nutrients in the conventional crops such as rice, wheat corn, tubers and other grains are predominantly carbohydrates as they are primary constituents which despite of the equal significance of proteins and lipids their occurrence stands comparatively limited, with soybeans serving as the predominant source for these crucial components, particularly sought after for their protein content within the biomass [25]. Providently algae presents a viable solution as they contain significantly high levels nutritionally available, digestible, and adequate [26]. Remarkably, certain algae species are already integrated as food supplements to augment the nutritional profile of various consumables, including cereal-based products, dairy derivatives, and even meat-based items. (C Aware). Noteworthy is the exceptional protein content of algae, comprising all essential amino acids crucial for human dietary needs, frequently at levels comparable to or exceeding those found in conventional crops [27,28].

3. FUNCTIONAL LIPID PRODUCTION

Functional lipids are an element or ingredient of functional foods. Algae particularly MiA are contain high amount of carotenoids and Omega-3 polyunsaturated fatty acids (PUFAs) which are widely known illustrations of useful lipids [29]. Terpenes, phospholipids, glycolipids, sulpholipids and sterols constitute further examples of functional lipids [30]. Marine MiA are the main producers of omega-3 polyunsaturated fatty acids (PUFAs), with lower concentrations found in marine macroalgae (2-4.5 % on dry weight basis) [31,32]. 68 PUFAs have been identified in MiA include docosahexaenoic acid and eicosapentaenoic acid [33] and γ-linolenic acid [34]. As reported by Barba et al., [35], certain green MiA (Chlorella sp., Haematococcus pluvialis) are excellent carotenoid producers. The lipids from MiA have been found to possess anti-cancer and anti-inflammatory and anti-viral activities as well as anti-oxidant potential making them feasible for nutraceutical and pharmaceutical applications. They also have presented anti-hypertensive effect [36], anti-diabetic effect [37], cardioprotective effect [38,39,40].

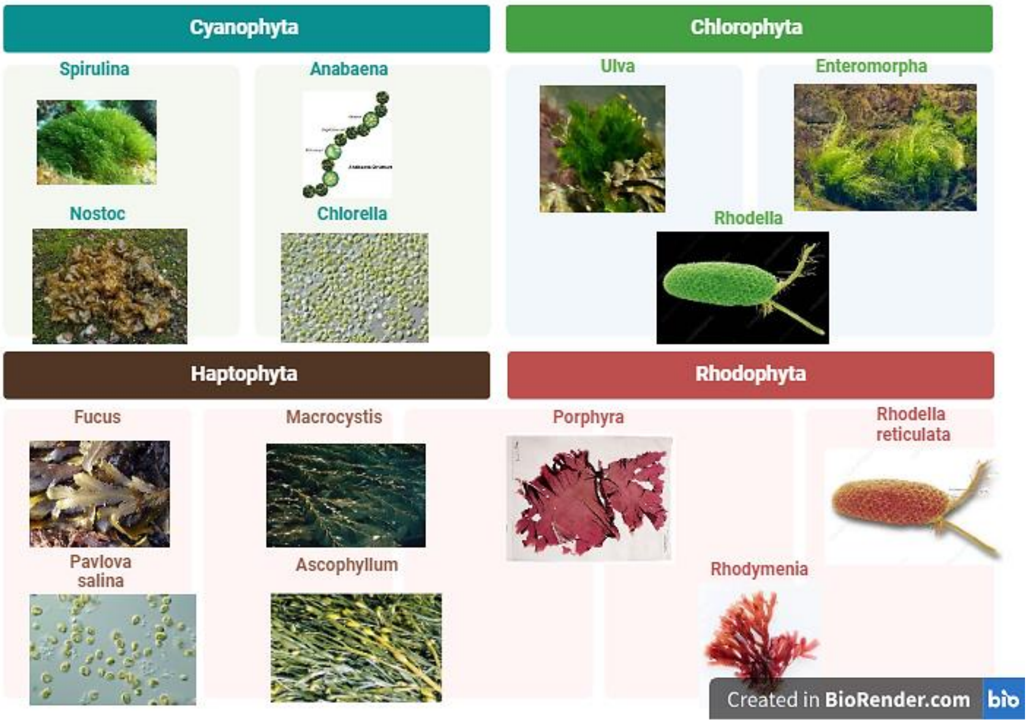

Fig. 1. Classification of algal species

However, lipids extraction is considered a crucial step as it poses difficulties owing to the thickness of polysaccharide and cellulose comprising cell walls which have excellent photosynthesis performing potential and its major fraction is lipids, proteins, and polysaccharides It makes up about 10% of the dry eight of the algal species and the composition varies depending on species and cultivation conditions [41,42,43]. Lipid content in algal species is generally in the range of 40 to 80 % which is higher than almost all the plant source indicators [44]. Several conventional and novel approaches have been studied and discussed for the extraction of lipids from the algal biomass, and employing eco-conscious methodologies for the extraction of compounds from microalgal biomass holds significant importance [45]. Some electrotechnology based techniques for cell disruption such as high-voltage electric discharge utilized in the studies by zhang et al. [46], which portrayed increased efficiency of solvent extraction of carotenoids, chlorophyll and other lipids. Han et al. [47], pulsed electric field (PEF), High-voltage electrostatic field, and comparatively novel technology such as supercritical fluid extraction, Assisted extractions (microwave, radiofrequency, Ultrasound and, enzymatic) pressurised liquid extraction and ohmic heating have been studied [48]. PEF is among the most popular techniques due to its energy efficiency (4.8 % the energy consumption as compared to the other methods) wherein several short pulses of high-intensity electric fields (20–50 kV cm^{-1}) between 2 electrodes usually in the range of µs to ms. Kumar et al. [49], Zuorro et al. [50], Qiu et al. [51] utilized EAE alone or in combination with the other methods of such as ultrasound or high-pressure homogenization [52,53]. The objectives can be attained through the application of cellulases or proteinases, or through the utilization of mixture containing multiple enzymes, such as cellulase combined with proteinase, or cellulase with mannanases, or a composite of other hydrolytic enzymes [54,55]. EAE is an expensive method, but it is also a quick, highly selective, and nontoxic approach that can be used in algae biorefinery [56]. Any method capable of attaining satisfactory levels of selectivity and resolution should be deemed useful, for extraction of functional bioactive oil. SFE has also demonstrated utility in separation of chlorophyll and carotenoid, exhibiting greater efficiency in carotenoid recovery compared to traditional UAE [57]. According to Savoire et al. [58], the nonpolar properties of CO2 render ScCO2 a suitable extraction solvent for semi-selective TGA extraction, preventing the extraction of phospholipids and other polar lipid classes [59,60]. Because of this, SCCO2 is a more appealing technique than traditional solvent approaches for precisely isolating triacylglycerols (TGs) from polar lipids [61]. Considerable decrease in extraction time during extraction of carotenoids and kavalactones using Fluid extraction was reported under pressure from H. pluvialis and Dunaliella salina (20 minutes in comparison with 90 minutes for UAE methods [62], making the procedure appropriate for thermolabile compounds, while consecutively reducing solvents quantities. The primary drawback inherent in employing the SFE lies in its high energy demands, thereby exerting a pronounced impact on the overarching operational efficacy. Advancements in lipid extraction methodologies have yielded innovative approaches circumventing solvent utilization, i.e., by isotonic extraction, osmotic pressure extraction, and enzyme-mediated extraction techniques [63]. The PLE procedure's selectivity can also be improved by utilizing solvent mixes [64]. However, the significant costs of extraction owing to the drying procedure prevent its commercialization, however, the extraction from wet biomass has emerged as a potential solution [65].

4. VITAMIN PRODUCTION

A variety of chemical compounds that serve as vital micronutrients for life are included in the class of vitamins [78]. These molecules perform a diverse array of biological functions, serving as coenzymes, antioxidants, hormones, cell signaling mediators, and regulators of the cells and tissues growth or differentiation [79]. The majority of the vitamins are of photosynthetic origin, whereas vitamins B and vitamin K are acquired through diet and primarily synthesized by bacteria [80]. Vitamins are essential for life, but neither humans nor animals can synthesise them very well, so they must be continuously ingested through food, such as plants, fruits, or seeds [81]. It is highly advised that people consume diets rich in various vitamins to prevent vitamin deficiencies in humans. Nevertheless, not all plants possess every vitamin, and certain vitamins such as D and K, along with several B vitamins, are rarely present in plant sources [86]. Algae (marine and terrestrial) are appreciated for synthesizing a wide array of vitamins, and MiA— photosynthetic, unicellular, rapidly dividing organisms—may prove to be particularly

Table 1. Extraction technology of lipids from algae, operations conditions and major findings

Extraction technique	Algae	Target lipids(s)	Operation conditons	Main findings	References
PEF	Chlorella	Carotenoids and chlorophyll	50 % DMSO; 3 kV/cm; 99 kJ/kg 44 pulses, for 0- 180 seconds	Extraction of target lipids was affected by the solvent and increase in content from 0-180 seconds for all the lipids	[66]
PEF	*Chlorella zofingiensis*	Carotenoids and chlorophyll	Ethanol; 20 kV; 50 pulses; 30-150 μs	Treatment with fifty kV utilizing 50 pulses was most efficient for the extraction which is eco-friendly	[67]
HVED	Phaeodactylum tricornutum	Lipids	CHCl3/MeOH (2:1 v/v) for lipids and 95 % EtOH for pigments; 40 kV; 200 pulses at 1-3 min interval; 0.1-8 ms	HPH was more suitable as compared to HVED for extraction of pigments (carotene and chlorophyll) and lipids	[68]
PLE	*Galdiera phlegrea*	Carotenoid	Ethaanol; pressure at 100 bar; at 50 °C temperature for 30 minutes	12 % enhancement in the yield of lipids as compared to conventional methods	[69]
EAE coupled with deep eutectic solvents	D*unaliella salina*	Carotenoids and lipids	Choline chloride with urea/ oxalic acid;	67.41 % ± 6.07 recovery achieved; 1 pot method prevented carotenoid loss	[70]
EAE	*Euglena gracilis*	Paramylon	n-hexane/Ethanol	Increased rate of extraction for lipids from 73% - 96% (paramylon at 58.3%)	[71]
EAE	*Nannochloropsis* sp.	EPA rich oil	Trichoderma sourced Cellulases; 50 °C; 12 hours	Enzyme assisted extraction extract yielded 77% TFA with 11% EPA fraction	[72]
UAE	Microchloropsis gaditana	glycolipids	Ethanol; 37 kHz; 100W; at 50 ◦C for 30 min	185% yield was achieved in comparison to traditional extraction	[73]
UAE	*Nannochloropsis*	lipids	hexane/isopropanol ;0.45 W/mL	Some positive impact on yield recorded, attributed to ultrasonic heating	[74]

Extraction technique	**Algae**	**Target lipids(s)**	**Operation conditons**	**Main findings**	**References**
UAE	*Chlorella* sp	PUFA	EtOH, CPME, DMC, 2-MeTHF; 20:1 (v/w); 60 ◦C; 40 minutes	Ethanol-2-MeTHF-extracted lipids showed dominance in linoleic acid, α-linolenic acid, and palmitic acid	[75]
MAE	*Nanochloropsis* sp.	EPA	2:1 (IL:biomass) 90 °C; 25 min, 3.3% w/v solid-loading	37.28 mg g^{-1} was the yield of EPA which was 8.1 times as opposed to Soxhlet extraction	[76]
SFE	*Chlorella vulgaris*	Carotenoid, chlorophyll	CO_2/EtOH; 250 bar, 60 °C; 100 kg_{CO2}/kg_{biom}	β- carotene- 24.88 mg/g; Chlorophyll- 7.06 mg/g; SFE presented short duration operation	[77]

beneficial as vitamin producers [82], .One such example of MiA is the vitamin-rich Spirulina platensis, which is already well-known as a "super food." Vitamins like B12 (active and bioavailable form contained by *C.vulgaris*), K, or D that are absent from higher plants can be found in MiA [83,84,85]. Marine microalgae have the capability to synthesize and accumulate a diverse array of vitamins, including pro-vitamin A, several B-group vitamins (B1, B2, B3, B5, B6, B8, B9, and B12), vitamin C, and vitamin E, among others. This synthesis and accumulation are correlated with the growth phase (Some vitamins such as C and E were most adequately harvested during exponential phase whereas, extraction of provitamin A and B2 was inefficient during stationary phase) and prevailing growth conditions [86]. Vitamin B6 and B9. Variation in different photic conditions induced varying vitamin concentrations for different species [87]. Pseudo form of vitamin B-12 furnishes false positive results which forms the base of vague claims regarding nutritional supplements thus, a credible method for analysis of the same is required [88,89]. A decline in vitamin E synthesis was attributed to the intensity of photons received by the reactor whereas the administration of UV-B light ≤ 4.4 kJ/ m^2 in Chlorella vulgaris improved the production of provitamin-A and Vitamin-E [90]. Contrarily, it was found to increase with decreasing nitrogen concentration in the media. All these findings indicate that vitamin expression is a species-dependent process and is modulated by environmental conditions, such as light and nutrient availability, as well as the harvesting stage. Different Microalgal sources have been found suitable for different vitamins such as spirulina for Vitamin B2, Chlorella for B3, N. gaditana and Chlorella sp. for B9 (6 times higher in comparison to spirulina powder i.e., 20.8 µg g^{-1} and 25.9 µg g^{-1} respectively). Also, Vitamin K1 which is predominantly synthesized via chemical protocols has been procured in significant amounts from cyanobacterial algae Anabaena cylindrica (200 µg g^{-1}) using photobioreactors.

However industrial microbial fermentation has only been established to produce a few vitamins such as vitamin K2 using engineered strains of Bacillus subtilis, vitamin B12 using Sinorhizobium meliloti, Propionibacterium shermanii, and Pseudomonas denitrificans, vitamin B2 using the filamentous fungus Ashbya gossypii and Bacillus subtilis, and vitamin C using Ketogulonicigenium vulgare, Bacillus megaterium and, Gluconobacter oxydans.

$SCCO_2$ based SFE was utilised for extraction of fat-soluble vitamins from *Tetradesmus Obliquus* by Chronopoulou et al. [91] and they found the treatment with 30 MPa pressure at temperature of 40 °C to be the best condition for extraction. Nanochlorosis oceanica was cultivated for the production potential for production of vitamin D3.

Vitamin-A concentration was found to be high in diatoms specially genus Chaetoceros (0.52 -0.97 mg/g dw basis) and, in Porphyridium a red microalga (upto 0.75 mg/g dw basis) [92]. Vitamin A content strongly varied among and inside algal classes hypothesizing that no link between vitamin A concentration and microalgal divisions do exist. [90]. A conversion factor between dry and fresh weight for MiA of around 10%, furnishes 0.42 and 0.1 mg of retinol equivalents on fresh weight basis per gram (mg RE/g FW) in Chaetoceros and Tetraselmis. [90]. The recorded values significantly surpass those documented in edible carrots, approximately 0.011 mg RE/g FW, and oranges, 0.0003 mg RE/g FW. Certain macroalgae species like P. vulgaris and P. palmata demonstrate noteworthy levels of vitamin B12 content. Furthermore, analyses have identified the presence of retinol, α-tocopherol, and ergocalciferol in C. barbata. Notably, algae boast significant concentrations of antioxidant vitamins C and E. Vitamin C plays a pivotal role in warding off scurvy, while vitamin E aids in the management of neurological disorders stemming from impaired nerve conduction, alongside anemia resulting from oxidative harm to red blood cells [86]. Luhila et al. [93] studied the vitamin B12 composition of Baltic algae for the omega-3-fatty acid content and reported *F. vesiculosusn* as the best source among the target species with 5.19 ± 0.32 mg/g on dry weight basis. Eliason studied *Emiliania huxleyi* for vitamin-D content and found that D1 and D2 were produced by the algae to the UV response and is a source for extraction of vitamin-D in its various forms. Anabeana cylindrica was cultivated by Tarento et al. [94] using modified ASM1 media under photoautotrophic conditions and monochromatic white light at 320 µmol photon/m2/s with dark:light cycle of 12/12 h at 23°C, and were able to achieve the content of 200 µg g^{-1}. Similarly, Nanochlorosis oceanica was studied as a natural source for vitamin D3 production. 1 µg g^{-1} of vitamin was produced by the biomass which suggest the suitability for production [95].

Table 2. Vitamins found in various algae species

Vitamin	Algae (Genus)
Vitamin-A	Arthrospira, Porphyridium, Chaetoceros, Euglena
Vitamin- D_2 and D_3	Arthrospira, Tetraselmis, Skeletonema, Pavlova
Vitamin E	Anabaena, Coccomyxa, Chlorococcum, Synechococcus
Vitamin K1	Arthrospira, Anabaena, Tetraselmis
Vitamin C	Anabaena, Chlamydomonas, Nannochloris, Stichococcus, Nannochloropsis
Vitamin B complex	Aphanizomenon, Dunaliella, Pavlova, tetraselmis

5. BIOACTIVE PHENOLIC COMPOUND EXTRACTION

Secondary metabolites such as phenolic compounds (PCs) in algae are indirectly involved in primary life processes of metabolism such as cell division, photosynthesis, and reproduction [96]. PCs are found in many algal families and consist of one or more than one phenolic rings, may or may not be halogenated to bestow distinct and frequently stronger biological activity [55]. Both red and brown algae contain phenolic terpenoids. For instance, Sargassaceae contain only meroladiterpenoids (chromanols, plastoquinones and, chromenes), whereas primarily red algae contain diterpenes [97]. Rhodomelaceae (Laurencia sp.) contains sesquiterpenes, and Callophycus serratus (bromophycolides) forms a macrolide as a result of secondary cyclization. phloroglucinol polymers Phlorotannins including fuhalols,fucols, eckols, phlorethols and, carmalols are major phenolic chemicals identified till now in the Phaeophyceae [98]. They exhibit a wide range of applications; for example, purified PCs portray antiradical, antioxidant, metal-chelation, UV-protective, and antifouling activity, and their activity varies according to molecular-size profile and concentration [99]. Microalgal and cyanobacterial biomasses are processed, primarily by cell disruption, to optimise the yield of phenolic extraction [100].

Various techniques of disruption have been devised for each microalgal group, owing to variations in the composition of their cell walls. The physical approaches include mechanical disruption and/or thermal therapy (high, mild, or freezing temperatures, occasionally through a thermal cycle) [101]. One type of liquid nitrogen heat treatment (−196 °C) for macroalgae and MiA is called cryogrinding [102]. Using high pressure (as in the French press) or bead milling, mechanical pretreatment breaks the cells. Microwaves are being used more and more, and their value has been shown in the extraction of pigments from diatoms, particularly fluoxanthin, β-carotene, and chlorophyll a [103], [104]. Ultrasonication is actually the most widely used disruption technique for phenolic research. As chemical cell disruption can be more selective than physical approaches, it has been extensively investigated; nonetheless, as this pretreatment is part of the extraction protocol [105,106].

5.1 Antioxidants

Antioxidant chemicals can be found in seaweeds. Glutathione (GSH) and ascorbate (vitamin C) are found in fresh seaweed biomass [107]. In addition, a variety of secondary metabolites with antioxidant properties can be produced by algae, such as carotenoids, tocopherol, polyphenols including flavonoids, catechins, lignans, tannins, and chlorotannins, and mycosporine-like amino acids [108]. Phlorotannins, or brown algal polyphenols, are one particular category among them. It has been noted that brown algae have the highest chlorotandin content of all marine algae [109]. These are 1,3,5-trihydroxybenzene oligomers, with a few exceptions. Eckol, phlorogluconol, dieckol, 6,6-bieckol, and chlorofucofuroeckol from Ecklonia sp.; dioxinodehydroeckol, 7-phloroeckol from Eisenia bicyclis, and diphlorethohydroxycarmalol from Ishige okamurae are the well-researched phlorotannins obtained from macroalgae [110.]

5.2 Diterpenes

Dictyotaceae is a family of algae that can create diterpenes and other secondary metabolites. Hydroazulenoids, xenicanes, dolabellanes, and so-called extended sesquiterpenoids are among the several forms that can be identified. Dictyota ciliolate, a marine brown algae, was used to extract diterpenes such as Dictyodial, Dictyol C, and Dicytol H. It has been found that they have algicidal, cytotoxic, and antiviral properties [111]. For instance, herpes simplex virus type 1 infection in Vero cells was suppressed by dierpenes isolated from Dictyota pfaffii and Dictyota menstrualis. Diterpenes from D.

menstrualis were tested for HIV-1 resistance [112,113,114].

5.3 Plant Growth-Promoting Substances/ Hormones

All bioactive substances that were separated from the aforementioned algae are mostly advantageous to both people and animals [115]. It's important to consider that algae are also a significant source of chemicals and hormones that promote plant growth [116]. These have been found in certain seaweed extracts derived from different kelp species, as well as in green, brown, and red seaweeds [117], [118]. Commercial applications for these algae extracts include crop production system amendments and growth stimulants. Numerous review publications have provided extensive descriptions of these plant growth-promoting chemicals/hormones, which include auxins, betaine, cytokinins, abscisic acid, gibberellins, ethylene, and polyamines [119,120]. The amount and kind of growth-regulating chemicals, particularly PGRs, that are present in seaweed biomass are currently the subject of extensive research [121].

6. SINGLE CELL PROTEIN PRODUCTION

Owing to their excellent production without arable land achieving a high protein content of up to 70%, unicellular microorganisms (cyanobacteria and MiA) have emerged as alternative protein sources [122]. In the same light the proteins from MiA are being proposed as a better protein source based on numerous analyses [123]. Single-cell proteins, often known as pure proteins or dried cells, are extracted from high-protein bacteria.

Chlorella, *Scenedesmus*, *Chlamydomonos*, *Spirulina*, *Nostock* etc., are MiA which constitute all essential amino acids— isoleucine, valine, threonine, leucine, lysine, methionine phenylalanine [124]. Compared to forages, high protein containing SCPs with adequate amino acid profile have present higher protein: carbohydrate ratio, a low lipid content, making them particularly appealing as dietary supplements for humans [125]. Fermentation serves as primary operation for production of SCP [126]. The selection of substrate is based on several factors, including cost, availability, the amount of oxygen needed for fermentation, the amount of heat generated, the fermenter's cooling capacity, and the cost of post-treatment processing [127]. When the fermentation process is finished, the available biomass is harvested and used as a source of protein. This microalgal biomass at adequately high concentrations has shown the yield of 22 to 44 tonnes hectare^{-1}. Purification, cell disruption, washing, and protein extraction are further processes used to further prepare the biomass to achieve high production rates and high yields [128,129]. Micro-algae produce protein rich cellular biomass containing a significant amount of SCP up to 70% by utilizing solar energy. Yields from micro-algae mass culture are 20–50 times higher than those from soybeans [130]. **V**arious crude substances serve as growth mediums for cultivating micro-algae for production of SCP. In the case of Chlorella, scholarly sources mention tempeh waste, containing 52% protein content; tofu waste, with 52.32% protein content; and cheese waste, with a total protein content of 15.43% [131]. Additionally, wastewater has been identified as a viable medium for cultivating Scenedesmus obliquus green algae, resulting in a protein content yield of 52%.

For Arthrospira (Spirulina) platensis cyanobacteria, SCP yields range from 48.59% to 56.17% by dry weight, contingent upon the specific culture medium employed [132,133,134]. Although various species of MiA, including Chlorella, Arthrospira, Haematococcus, Dunaliella, and Schizochytrium, are designated as Generally Recognized as Safe (GRAS) by the United States Food and Drug Administration (FDA), their utilization in commercial food and feed formulations requires thorough scrutiny due to potential toxicity concerns. Furthermore, the high nucleic acid content in the algal cells which could lead to kidney related disorders and gout, and high content of chlorophyll responsible for bitterness also, serve as barriers to their application in formulation of food/ feed supplements [135]. Moreover, mild pretreatment strategies have been devised to reduce to minimum or nullify the nucleic acid content from the final product. Closed photobioreactors (flat plates, air-lift reactors, tubular systems, bubble columns, large plastic bags) can be engineered for industrial-scale operations. Scalability can be achieved by replicating multiple units.

6.1 Challenges

The microalgal cultivation and the development of biorefinery based systems have attracted significant attention for their potential to produce high quantities of value-added compounds, including pigments, vitamins, polyunsaturated fatty acids (PUFAs), and antioxidants [141] .However, several challenges remain partially or unaddressed in this field. The scaling up of algal cultivation is a costly and complex endeavor which requires the optimization of various factors such the methods, approach and system, the strategies for cultivation and harvesting (mechanical methods like filtration, centrifugation etc,) and chemical (flocculation, coagulation, etc.) methods for biomass harvesting. These processes are estimated to contribute 20–30% to the overall production costs), biomass cultivation, conditions of cultivation (temperature, time light and agitation method and intensity and nutrients) and monitoring the potential environmental risks to be successful and thus is economically not feasible.

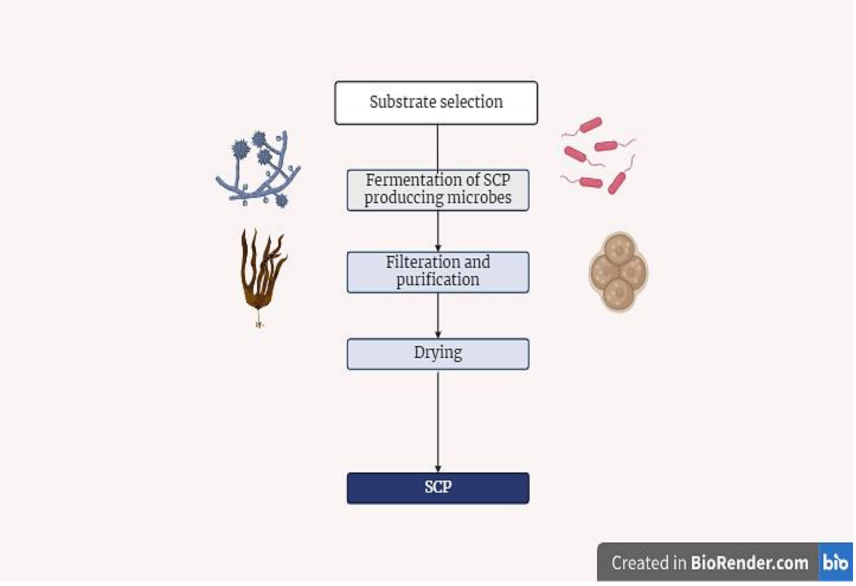

Fig. 2. General production process for SCP from different microorganisms

Table 3. Algal species being used for single cell protein production

Algae species	Media	Protein content	Important findings	Reference
MiA and methanotroph system	Activated biogas sludge	0.51g/g biomass	Increased iron availability stimulated increased growth; Limited nitrogen reduced the growth and protein content upto 0.31g/g	[136]
Chlorella vulgaris and Yarrowia lipolytica	Liquid digestate of dairy wastewater	0.51g/g biomass	Enhanced biomass and protein yields were achieved by mixed culture as compared to C.vulgaris culture	[137]
Chlorella vulgaris and Arthrospira sp.	Struvite (Phosphorus obtained from wastewater treatment)	-	The protein content of MiA cultivated on struvite was consistently comparable to that obtained when grown on standard media.	[138]
Chlorella vulgaris	Electrochemically treated potato juice wastewater	0.52g/g biomass	The bioelectrochemical assistance resulted in enhancing the suitability of wastewater by achieving high rates of removal for COD, TKN and Phosphorus, for pure protein production	[139]
Chlorella sorokiniana	Strong swine wastewater	0.59	pH had a significant impact on productivity	[140]

Efficiency of extraction, which is dependent on the technology of extraction, The hydrocolloidal nature of algal biomolecules, size and compatibility, down streaming processing and recovery of compounds and energy consumption remain as viable concerns as they impact the consumption patterns and selection of the algal compounds for selection. In the food industry, algae cultivation must adhere to the regulations set by the Food and Drug Administration (FDA) to ensure the safety of algae extract for human consumption. Identification of an efficient technique for separation of target compound from algal suspension is crucial in microalgal biomass production, given the substantial environmental and economic costs involved.

7. CONCLUSION

Current trends of data available on the per capita availability of food resources directs towards a scarcity of production both as food stock and feedstock i.e., the current food production capacity and potential is not completely sustainable to contain and fulfill the enormous increment in requirement of food (25% - 70%) relative to the rising population, expected to be at 9.7 billion by 2050, neither quantitatively nor qualitatively. Most of the organisms belonging to the algal constitution are aquatic and photosynthetic in nature, but a few are terrestrial. They possess the potential of furnishing a biomass rich in carbohydrates, lipids and proteins utilizing sunlight and CO_2. Commercial applications for algae biomass include human nutrition, animal feed, cosmetics, bio-fertilizers, pigments, biofuels, and nutraceuticals. Functional lipids being extracted from the algal sources are PUFAs (EPA, DHA), MUFAs, Carotenoids, Chlorophyll etc. Electrostatic, enzyme assisted, solvent based and modified solvent-based treatments have been utilized for extraction, which have significant advantage over the existing conventional techniques. Vitamins are essential for life, but neither humans nor animals can synthesise them very well, so they must be continuously ingested through food, such as plants, fruits, or seeds. Marine algae are known to produce a wide variety of vitamins, and MiA—photosynthetic, unicellular, rapidly dividing organisms—may prove to be particularly beneficial as vitamin producers. Phenolic compounds are found in many algal families and consist of one or more phenolic rings. These rings can be halogenated to bestow distinct and frequently stronger biological activity. Cryogrinding, bead milling, and other novel methods have been and are being utilised for the extraction. Because of their efficient development independent of arable land and high protein content of up to 70%, unicellular organisms such as MiA and cyanobacteria have arisen as alternative protein sources. In the same light the proteins from MiA are being proposed as a better protein source based on numerous analyses. Micro-algae can produce cellular biomass containing a significant amount of SCP (up to 70%) by utilizing solar energy. Yields from micro-algae mass culture are 20–50 times higher than those from soybeans. Thus, the utilization of algae for production of a plethora of nutrient rich biomasses is crucial for making the food systems more efficient and the food nutrient pool more versatile and easily available.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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