Review Article

Utilization of Algae for Nutrient-rich Biomass and Bioproducts

Abstract

The diminishing food resources owing to increasing population presents the requirement for novel sources of nutrition. Micro and macro algae are emerging as potential candidates of food, feed and other industries owing to their properties mentioned in the article.The existing literature was reviewed for the production, processes techniques and technologies for efficient utilization of algal biomass in various fields directly or indirectly related to food industry such as for extraction of functional lipids, vitamins, Bioactive phenolic compound extraction (Antioxidants, diterpenes and plant growth regulating substances) and, Single cell proteins (SCPr).The algae is found to be an efficient alternative source to the existing sources for nutrient, food formulation, food ingredients extraction, Extraction of bioactive and functional compounds for nutraceutical and pharmaceutical applications. Novel emerging technology has allowed for the most efficient extraction of these compounds leading to establishment of a sustainable and circular economy.The utilization of novel techniques such as SFE, UAE, MAE, PLE etc., for extraction, separation and purification of desirable target compounds from algae has the potential of replacing the existing conventional sources with algae which is highly adaptable, versatile, efficient in growth patterns and high in productivity.

***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%) (Hunter et al., 2017) 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 (WHO, 2020). 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. (Jones et al., 2020; Bertsch et al., 2021). There is a tremendous diversity of micro-algae (MA) species, with a high occurrence in the marine systems, fistramenopiles such as Chaetocerosmuelleri, and Thalassiosirapseudonana and dinophyta such as Crypthec are dominant in marine systems (Heimann et al., 2015; Labeeuw et al. 2017; Minggat et al. 2021; Kumaran et al. 2021).

Most of the organisms belonging to the algal constitution are aquatic and photosynthetic in nature, but a few are terrestrial. (Gerotto et al., 2020). 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 (Khan et al., 2018; Katiyar et al. 2021). 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. (Premaratne et al., 2022; Sarma et al., 2021). Algae biomass is commercially utilized in human nutrition, nutraceuticals, pigments, biofuels, animal feed, cosmetics, and bio-fertilizers (Suganya et al., 2019; Garcia et al., 2018). Algae and cyanobacteria pose versatile advantages which deem them suitable for aforementioned applications. Fistly, water serves the purpose of electron donor for oxygenic photosynthesis also, the present an inordinate biomass productivity/ acre in comparison to oilseed crops and such yield is not achievable using current agricultural systems, Moreover, they are a nonfood feedstock thus are resolution for food vs feed resources. Their culture is rapid and doesn't require agriculture land, they are efficient adaptors of growth conditions such as seawater, brackish water, and wastewater. Finally, they can be utilized to formulate a diverse array of products of sustainable nature (Nguyen and Hoang, 2016; Bhowmick et al., 2019; Haeder et al., 2022; Khan et al., 2018; Shin et al., 2018;; Hosain et al., 2019; Yap et al. 2021).

Microalgal biomass has been portrayed as a sustainable alternative for conventional sources of biofuels, several food and feed systems. (Lever et al., 2020) 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. (H Onyeaka et al., 2021).

The industrial application requires cultivation at a mass level which encounter the cost constraint in comparison to the raw materials of other origin for similar purposes. (Roostaeie et al., 2018). Enhancing cost-effectiveness and economic feasibility of utilizing microalgae 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 microalgae biomass utilization. And lastly, enhancing the completeness of extraction of target compounds from the biomass. (Rafa et al., 2021; Gu et al., 2023; Ahmad et al., 2022)

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.

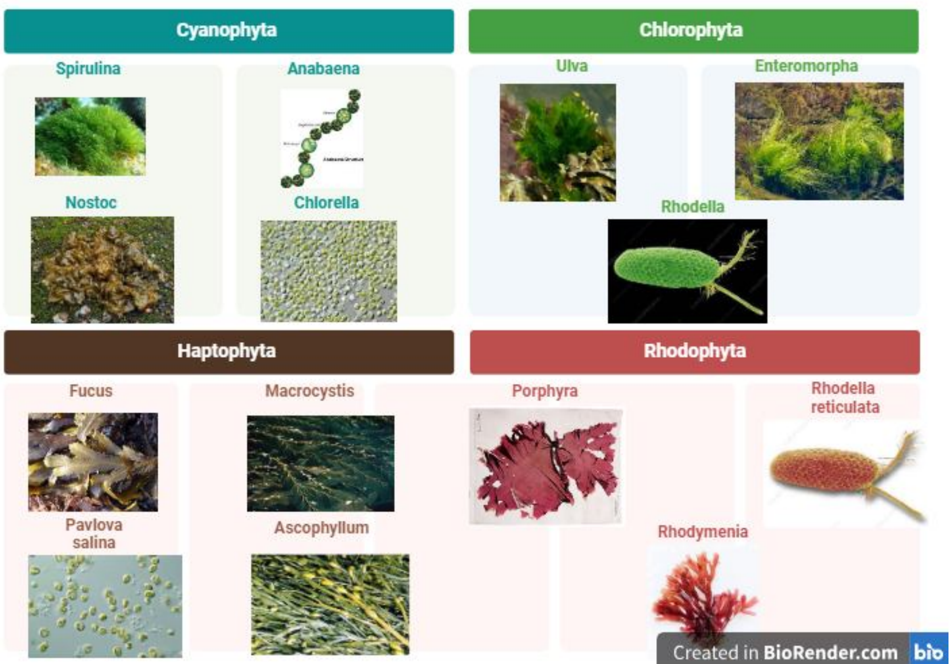

Figure 1 Classification of algal species

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. (Verma et al., 2018). Providantly algae presents a viable solution as they contain significantly high levels nutritionally available, digestible, and adequate. (Fernandez et al., 2023). 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 (P Geada et al., 2021; Quintieri et al., 2023).

3. Functional lipid production

Functional lipids are an element or ingredient of functional foods. Algae particularly microalgae are contain high amount of carotenoids and Omega-3 polyunsaturated fatty acids (PUFAs) which are widely known illustrations of useful lipids. (Remize et al., 2021; Ren et al., 2022). Terpenes , phospholipids, glycolipids, sulpholipids and sterols constitute further examples of functional lipids. (Domínguez et al., 2022). Marine microalgae 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) (Barta et al., 2021; Remize et al., 2021; Polat et al., 2020). 68 PUFAs have been identified in microalgae include docosahexaenoic acid and eicosapentaenoic acid and γ-linolenic acid. (Otero et al. 2018; Li et al., 2019; Kumar et al., 2019) As reported by Barba et al. (2015), certain green microalgae (Chlorella sp., Haematococcuspluvialis) are excellent carotenoid producers. The lipids from microalgae 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, anti-diabetic effect, cardioprotective effect. (Carrizzo et al., 2020; A Saide et al., 2021; Rehmanji et al., 2022; Silva et al., 2024).

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 (Rösch et al., 2018; Oh et al., 2022; Abolore et al., 2023). Lipid content in algal species is generally in the range of 40 to 80 % which is higher than almost all the plant source indicators. (Morales et al., 2021). 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. (Singh et al., 2021; Mago et al., 2023). Some electrotechnology based techniques for cell disruption such as high-voltage electric discharge utilized in the studies by zhang et al. (2020), which portrayed increased efficiency of solvent extraction of carotenoids, chlorophyll and other lipids. Han et al. (2018), 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. (Pereira et al., 2023;).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. (2017); Zuorro et al. (2016); Qiu et al. (2019); Wang et al. (2015) utilized EAE alone or in combination with the other methods of such as ultrasound or high-pressure homogenization (Liang et al. 2018; Wang et al. 2017). 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. (Chukwuma et al., 2020; Jayasekara et al., 2019). EAE is an expensive method, but it is also a quick, highly selective, and nontoxic approach that can be used in algae biorefinery (Kumar et al. 2017). Any method capable of attaining satisfactory levels of selectivity and resolution should be deemed useful, for extraction of functional bioactive oil (Satriana et al. 2019). SFE has also demonstrated utility in separation of chlorophyll and carotenoid, exhibiting greater efficiency in carotenoid recovery compared to traditional UAE (Sanchez et al., 2019). According to Cheng et al. (2016), 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. (Cecchi et al., 2021; Niemi et al., 2021). Because of this, SCCO2 is a more appealing technique than traditional solvent approaches for precisely isolating triacylglycerols (TGs) from polar lipids (Bjornsson et al. 2020). The authors reported considerable decrease in extraction time during extraction of carotenoids and kavalactones using Fluid extraction under pressure from H. pluvialis and Dunaliella salina (20 minutes in comparison with 90 minutes for UAE methods (Sarkarat et al., 2023), making the procedure appropriate for thermolabile compounds, while consecutively reducing solvents quantities. The PLE procedure's selectivity can also be improved by utilising solvent mixes (Attard and Hunt 2018).

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	Wang et al. (2023)
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	Pereira et al. (2024)

				extraction which is eco-friendly	
HVED	Phaeodactylumtricornutum	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	Zhang et al. (2020)
PLE	*Galdieraphlegrea*	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	Imbimbo et al. (2020)
EAE	D*unaliella salina*	Carotenoi	Choline chloride	67.41 % ± 6.	Asevado et

coupled with deep eutectic solvents		ds and lipids	with urea/ oxalic acid;	07 recovery achieved; 1 pot method prevented carotenoid loss	al. (2023)
EAE	*Euglena gracilis*	Paramylon	n-hexane/Ethanol	Increased rate of extraction for lipids from 73% - 96% (paramylon at 58.3%)	Zheng et al. (2023)
EAE	*Nannochloropsis* sp.	EPA rich oil	Trichoderma sourced Cellulases; 50 °C; 12 hours	Enzyme assisted extraction extract yielded 77% TFA with 11% EPA fraction	Bhattacharya et al. (2023)

UAE	Microchloropsis gaditana	glycolipids	Ethanol; 37 kHz; 100W; at 50 ◦C for 30 min	185% yield was achieved in comparison to traditional extraction	Pühringer et al. (2024)
UAE	***Nannochloropsis***	lipids	hexane/isopropanol ;0.45 W/mL	Some positive impact on yield recorded, attributed to ultrasonic heating	Meinis et al. (2024)
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	
UAE	*Ulva lactuca*		40 KHz; 60 W; 1 h, 50% ethanol, and temperature of 25 °C was the optimized condition for	-	
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	Motlagh et al. (2024)
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;	Georgiopoulou et al. (2023)

	SFE presented short duration operation

4. Vitamin production

A variety of chemical compounds that serve as vital micronutrients for life are included in the class of vitamins. 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. (Mitra et al., 2022; Surana et al., 2023). Majority of the vitamins are of photosynthetic origin, whereas vitamins B and vitamin K are acquired through diet and primarily synthesized by bacteria. (Simes et al., 2020; Mondro et al., 2020). 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. (Ofoedu et al., 2021). 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. (Godswill et al., 2020). Algae (marine and terrestrial) are appreciated for synthesizing a wide array of vitamins, and microalgae—photosynthetic, unicellular, rapidly dividing organisms—may prove to be particularly beneficial as vitamin producers. (Edellman et al. 2019; Jung et al. 2019;) .One such example of microalgae 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 microalgae. (Islam et al., 2017; Wang et al., 2020; Jung et al., 2019; Edelmann et al., 2019; Kiran et al., 2021). $SCCO_2$ based SFE was utilised for extraction of fat soluble vitamins from *Tetradesmus Obliquus* by Chronopoulou et al. (2019) and they found the treatment with 30 MPa pressure at temperature of 40 °C to be the best condition for extraction.

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

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).

(Bhattacharya et al., 2022). Vitamin A content strongly varied among and inside algal classes hypothesizing that no link between vitamin A concentration and microalgal divisions do exist. (Mondro et al., 2020). A conversion factor between dry and fresh weight for microalgae 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. (Mondro et al., 2020). 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. (Godswill et al., 2020). Luhila et al. (2022) 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 *Emilianiahuxleyi*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.

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. 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. (Pereira et al., 2021). Both red and brown algae contain phenolic terpenoids. For instance, Sargassaceae contain only meroladiterpenoids (chromanols,plastoquinones and, chromenes), whereas primarily red algae contain diterpenes. (Junopia et al., 2020). 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. (Cotas et al., 2020). 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. (Kumar et al., 2021). Microalgal and cyanobacterial biomasses are processed, primarily by cell disruption, to optimise the yield of phenolic extraction (Kapoor et al. 2022).

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). (Saravana et al., 2023; Bharte et al., 2021). One type of liquid nitrogen heat treatment (−196 ∘C) for macroalgae and microalgae is called cryogrinding. 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. (Gallego et al., 2021; Mehariya et al., 2021). 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. (Nemre et al. 2021) (Khadhraoui et al., 2021; Saravana et al. 2023; Rahman et al., 2022 and Liu 2022).

5.1 Antioxidants

Antioxidant chemicals can be found in seaweeds. Glutathione (GSH) and ascorbate (vitamin C) are found in fresh seaweed biomass. (Begum et al., 2021). 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. (Kalasariya et al., 2023). 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. (Ummat et al., 2020). 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 Ishigeokamurae are the well-researched phlorotannins obtained from macroalgae. (Shrestha et al., 2021; Fernando et al., 2022)

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. (Gamal et al., 2023). For instance, herpes simplex virus type 1 infection in Vero cells was suppressed by dierpenes isolated from Dictyotapfaffii and Dictyotamenstrualis. Diterpenes from D. menstrualis were tested for HIV-1 resistance. (Rushdi et al., 2022; Cotas et al., 2022; Pagarete et al., 2021)

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. It's important to consider that algae are also a significant source of chemicals and hormones that promote plant growth. (Kapoore et al., 2021; Wang et al., 2021; Ammar et al., 2022). These have been found in certain seaweed extracts derived from different kelp species, as well as in green, brown, and red seaweeds. (Ali et al., 2021; Hurtado et al., 2021). 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. (Boukhari et al., 2020; Kholssi et al., 2022; Ammar et al., 2022). The amount and kind of growth-regulating chemicals, particularly PGRs, that are present in seaweed biomass are currently the subject of extensive research. (Ma et al., 2022; Parmar et al., 2023; Madruga et al., 2020)

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 microalgae) have emerged as alternative protein sources (Bratosin et al., 2021; Grossmann et al., 2019; Nyyssölä et al, 2022; Onyeaka et al., 2022). In the same light the proteins from microalgae are being proposed as a better protein source based on numerous analyses. (Buono et al., 2014; Wells et al., 2017). Single-cell proteins, often known as pure proteins or dried cells, are extracted from high-protein bacteria. *Chlorella*, *Scenedesmus*, *Chlamydomonos*, *Spirulina*, *Nostock* etc., are microalgae which constitute all essential amino acids— isoleucine, valine, threonine, leucine, lysine, methionine phenylalanine. (Nass and Nascimento, 2022; Quieroz et al., 2023). 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. (Jach et al., 2022; Bratosin et al., 2021). Fermentation serves as primary operation for production of SCP (Kadim et al., 2017). 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. (Siddiki et al., 2022; Varghese et al., 2022). When the fermentation process is finished, the available biomass is harvested and used as a source of protein. Purification, cell disruption, washing, and protein extraction are further processes used to further prepare the biomass to achieve high production rates and high yields (Dhaver et al., 2010; John et al., 2019; Rajput et al., 2024). Micro-algae produce protein rich cellular biomass containing a significant amount of SC

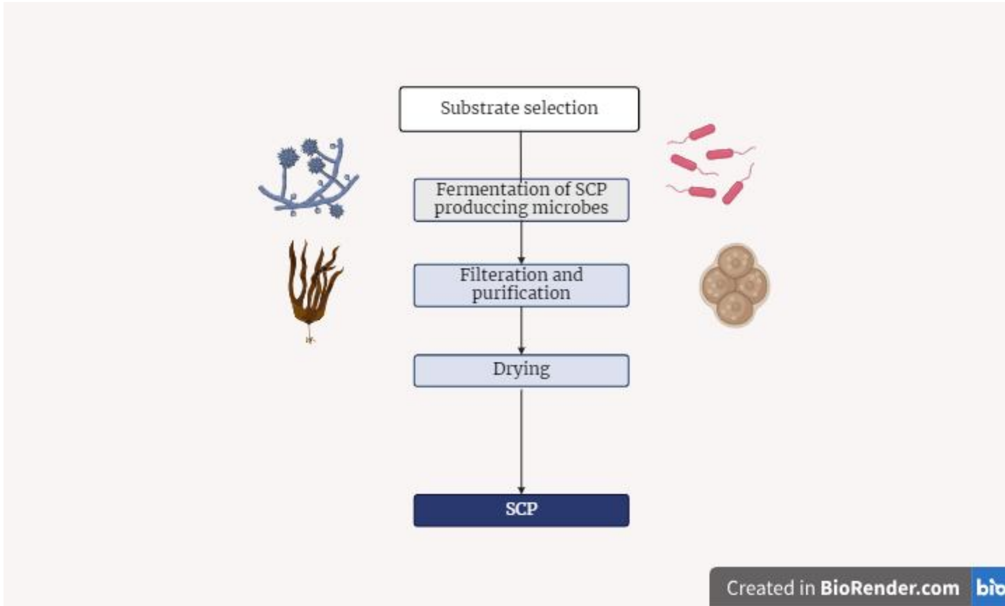

Figure 2 General production process for SCP from different microorganisms

P up to 70% by utilizing solar energy. Yields from micro-algae mass culture are 20–50 times higher than those from soybeans. (Hosseinkhani et al., 2022; Chronakis et al., 2018).

various 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%. (Baltork et al., 2022; Bratosin et al., 2021). 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. (Lopez et al., 2020; Singh et al., 2022; wang et al., 2022)

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 utilised for 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 microalgae—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 microalgae and cyanobacteria have arisen as alternative protein sources. In the same light the proteins from microalgae are being proposed as a better protein source based on numerous analyses. Micro-algae have the ability to 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.

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