Journal Pre-proof

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PII: S2589-014X(25)00166-5

DOI: https://doi.org/10.1016/j.biteb.2025.102184

Reference: BITEB 102184

To appear in: *Bioresource Technology Reports*

Received date: 10 February 2025

Revised date: 21 May 2025

Accepted date: 15 June 2025

Please cite this article as: H.H. Chung, L.W.K. Lim, Q.H.B. Zainol Abidin, et al., Microalgae: Recent micro to macro-applications in South East Asia, *Bioresource Technology Reports* (2024), https://doi.org/10.1016/j.biteb.2025.102184

Microalgae: Recent micro to macro-applications in South East Asia

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Abstract

Microalgae are unicellular organisms found in aquatic environments, playing a key role in carbon fixation and oxygen production through photosynthesis. They produce valuable bioactive compounds such as proteins, lipids, and antioxidants. Their wide-ranging applications make them a promising sustainable resource. In biofuel production, microalgae serve as an eco-friendly alternative to fossil fuels while aiding in carbon sequestration. In nutraceutical industries, they offer essential nutrients like omega-3 fatty acids and amino acids. The pharmaceutical sectors utilize microalgae-based nanocarriers for efficient drug delivery. Environmentally, microalgae are effective in wastewater treatment and bioremediation due to their pollutant-absorbing abilities. In Southeast Asia, the biomass energy market is expected to grow at 7.6% compound annual growth rate from 2025 to 2034 and recent studies highlight their growing role in addressing sustainability challenges. As research advances, microalgae continue to emerge as a powerful tool in promoting green technology and solving global environmental and energy issues.

Keywords: microalgae; nutraceuticals; sustainable; pharmaceutical; bioremediation

1. Introduction

Microalgae are a diverse group of microscopic photosynthetic organisms found in both freshwater and marine environments. They can easily thrive in various harsh growing environments, namely saline-alkaline soil, food waste, arid and semi-arid regions, wastewater and seawater, utilizing only limited nutrients [1]. They encompass a wide range of species, including cyanobacteria (blue-green algae), diatoms, green algae, and dinoflagellates, among others. Unlike macroalgae, or seaweeds, microalgae are typically unicellular and can exist as single cells, colonies, or simple multicellular structures. These organisms are capable of converting sunlight, carbon dioxide, and water into biomass through the process of photosynthesis, producing oxygen as a byproduct [2]. Unlike their larger counterparts, macroalgae, microalgae are microscopic and exist as single cells or simple colonies, making them highly adaptable to various environmental conditions. This ability not only makes them essential players in global carbon cycling but also crucial contributors to the production of oxygen in Earth's atmosphere [3].

The significance of microalgae extends beyond their ecological roles. They are a rich source of valuable compounds, including proteins, lipids, carbohydrates, vitamins, and pigments, which have a wide array of applications in industries such as food and nutrition, pharmaceuticals, cosmetics, biofuels, and environmental management (Figure 1). The rapid growth rates and high productivity of microalgae, along with their ability to grow in various environments, make them an attractive and sustainable resource for biotechnological innovations. As research and technology continue to advance, the potential of microalgae in addressing global challenges, including food security, renewable energy, and environmental sustainability, becomes increasingly apparent. In Southeast Asia, the biomass energy market is expected to grow at 7.6% compound annual growth rate from 2025 to 2034. In this review, recent microalgae applications across the globe and Southeast Asia countries were discussed.

2. Nutritional Supplements and Food Products

The microalgae are capable of the absorption and conversion of 11 percent of solar energy to chemical energy effortlessly. Interestingly, the annual biomass yield of microalgae can reach up to 3 to 500 tonnes which translates to 280 tonnes per hectare and dry matters of up to five thousand tonnes by mass [4]. Their exceptional nutraceutical production rates are so impressive that they are deemed the main players in circular bioeconomy that promises to reuse, recycle and recover, to name a few, such as *Dunaliella* sp., *Chlorella* sp., *Porphyridium* sp., *Scenedesmus* sp., *Chlamydomonas* sp., *Synechococcus* sp. as well as *Haematoccoccus* sp. [4.5].

Microalgae such as *Spirulina* and *Chlorella* are renowned for their exceptional nutritional profiles, making them popular as dietary supplements. *Spirulina*, for example, contains up to 70% protein by dry weight, including all essential amino acids, making it an excellent protein source for vegetarians and vegans [6]. It also provides a rich supply of vitamins, including B vitamins (such as B12), vitamin A (in the form of beta-carotene), and vitamin E. Additionally, microalgae are a valuable source of essential fatty acids, particularly omega-3 and omega-6, which are crucial for heart and brain health. These beneficial compounds can also aid in reducing the risk of neurodegenerative diseases like Alzheimer’s disease. Antioxidants like astaxanthin can cross the blood-brain barrier and protect the neurons from oxidative damage.

In the food industry, microalgae are increasingly incorporated into functional foods to enhance their nutritional value. For example, algae-derived omega-3 fatty acids, especially DHA (docosahexaenoic acid) and EPA (eicosapentaenoic acid), are commonly added to products like infant formula, dairy substitutes, and health bars [4]. The incorporation of microalgae not only boosts the nutritional content but also provides natural pigments, such as chlorophyll and phycocyanin, which can be used as natural food colorants. Moreover, their antioxidant properties help in preserving food quality and extending shelf life, making microalgae a versatile and beneficial addition to various food products [6]. Moreover, the glycolipids and polysaccharides yielded from microalgae can stimulate immune responses and strengthen the body's defense against infections and diseases. Phycocyanin from microalgae like *Spirulina* exhibit anti-inflammatory properties by downregulating and suppressing COX-2 enzymes. *Chlorella* can help in binding heavy metals and toxins in the gut, aiding detoxification. It also supports healthy gut microbiome, which is crucial for nutrient absorption, immune balance and mental health.

Across South East Asia countries, *Spirulina* sp. and *Chlorella* sp. are the most common candidate selected as major source of food supplement and nutraceutical, especially in Malaysia, Thailand, Philippines and Indonesia (Table 1). The major microalgae components that can be obtained from these species are protein, essential amino acids, starch, essential fatty acids, phycocyanin, polyunsaturated fatty acids, omega-3, lipid, carotenoids, vitamins as well as antioxidants. These selected microalgae species are mainly manufactured into nutritional capsules, staple food, food supplement and functional food products.

Table 1: Known / Recent microalgae nutritional / food supplement applications / products in South East Asia region.

No.	Species	Component / Characteristics	Extraction techniques; Application / Product	Company / Country	References
1	*Aurantiochytrium*	Fatty acids	Soxhlet extraction (n-hexane); Food supplement for human	Indonesia	[12]
2	*Chaetoceros (calcitrans)*	Antioxidants, carotenoids, chlorophyll, lipid, omega-3 fatty acids, omega-6 fatty acids, protein, xanthophyll	Three antioxidant chemical assays (thiobarbituric acid, ferric thiocyanate and 1, 1'-diphenyl-2-picrylhydrazyl); Functional food, used as natural sources of antioxidants with high nutritional value	Malaysia, Philippines	[8], [15]
3	*Chlorella (salina, sp., vulgaris)*	Antioxidants, carbohydrate, carotenoids, chlorophyll, immune stimulator compounds, lipid, minerals, omega-3 fatty acids, omega-6 fatty acids, polysaccharides, polyunsaturated fatty acids, protein, vitamins, xanthophyll	Three antioxidant chemical assays (thiobarbituric acid, ferric thiocyanate and 1, 1'-diphenyl-2-picrylhydrazyl); Functional food, potential for food supplement, used as natural sources of antioxidants with high nutritional value	Indonesia, Malaysia, Philippines	[7], [8], [11], [13], [14], [15]
4	*Chlorococcum (sp.)*	Lipid	Soxhlet extraction (dichloromethane:methanol (2:1)); Potential for food supplement	Indonesia	[9]
5	*Haematococcus*	Carotenoids, chlorophyll, lipid, protein, xanthophyll	Soxhlet extraction (acetone); Functional food	Philippines	[15]
6	*Indonesian microalgae*	Nutraceutical	(N/A); Functional food	Indonesia	[16]

7	*Isochrysis (galbana)*	Antioxidants, omega-3 fatty acids, omega-6 fatty acids	Three antioxidant chemical assays (thiobarbituric acid, ferric thiocyanate and 1, 1'-diphenyl-2-picrylhydrazyl); Used as natural sources of antioxidants with high nutritional value	Malaysia	[8]
8	*Klebsormidium (flaccidum GN-2)*	Starch	Supercritical carbon dioxide extraction; Staple food	Malaysia	[3]
9	*Nannochloropsis (oculata, oculata YG-2)*	Antioxidants, omega-3 fatty acids, omega-6 fatty acids, starch	Supercritical carbon dioxide extraction; Staple food, used as natural sources of antioxidants with high nutritional value	Malaysia	[3], [8]
10	*Pediastrum (spp.)*	Protein	Protein extraction kit; Food supplement for human	Thailand	[10]
11	*Spirulina (arthrospira platensis, arthrospira spp.)*	Algae extract, carbohydrate, carotenoids, essential fatty acids, lipid, phycocyanin, protein	Glycerol extraction; Frozen raw spirulina, functional food, nutritional supplement (capsule), nutritional supplement (tablet)	Brunei, Indonesia, Malaysia, Philippines, Thailand	[1], [4], [5], [6], [11], [15], [17]
12	*Scenedesmus (quadricauda, 276-3)*	Antioxidants, essential amino acids, omega-3 fatty acids, omega-6 fatty acids, protein, vitamins	Three antioxidant chemical assays (thiobarbituric acid, ferric thiocyanate and 1, 1'-diphenyl-2-picrylhydrazyl); Functional food, used as natural sources of antioxidants with high nutritional value	Malaysia, Thailand	[2], [8]
13	*Tetraselmis (tetrathele)*	Antioxidants, omega-3 fatty acids, omega-6 fatty acids	Three antioxidant chemical assays (thiobarbituric acid, ferric thiocyanate and 1, 1'-diphenyl-2-picrylhydrazyl); Used as natural sources of antioxidants with high	Malaysia	[8]

			nutritional value		

3. Biofuels

Microalgae have garnered significant attention as a sustainable source of biofuels due to their high lipid content and rapid growth rates. They are indispensable feedstocks for third- and fourth-generation biofuels with a excellent lipid yield of up to 70% on a dry weight basis [120, 145]. Unlike terrestrial crops used for biofuel production, microalgae do not compete with food crops for arable land and can be cultivated in a variety of environments, including freshwater, brackish water, and even wastewater. This flexibility reduces the environmental impact and enhances the sustainability of biofuel production [118]. The use of microalgae for biofuel production also contributes to carbon sequestration, as these organisms absorb CO_2 during photosynthesis [112]. This dual role of producing renewable energy and reducing greenhouse gases makes microalgae a promising candidate for addressing global energy and environmental challenges [112].

While microalgae are a promising source of sustainable biofuels due to their high lipid content and rapid growth, two major hurdles limit their commercial viability: high production costs and complex downstream processing. Firstly, cultivating microalgae on a large scale requires substantial inputs—nutrients, CO_2, light, and water—all of which contribute to high operational costs [112]. Photobioreactors, although more efficient than open ponds, are expensive to build and maintain. Moreover, achieving consistent, high-yield biomass remains a technical challenge under fluctuating environmental conditions. Secondly, downstream processing, which includes harvesting, drying, cell disruption, and lipid extraction, is energy-intensive and costly. Harvesting dilute algal cultures requires methods like centrifugation or flocculation, which are not economically feasible at scale. Lipid extraction often involves solvents and additional processing steps, further increasing the environmental and financial cost [112]. Despite their ecological appeal, microalgae-based biofuels face critical economic and technical barriers. Innovations in low-cost cultivation, integrated biorefineries, and efficient extraction methods are essential to make this technology competitive with fossil fuels and first-generation biofuels [118].

Microalgae such as *Scenedesmus*, *Chlamydomonas*, *Nannochloropsis* and *Chlorella* are highly capable of synthesising large quantities of lipids, which can be extracted and converted into biodiesel through processes like transesterification (Figure 2). Some species are capable of accumulating lipids up to 60% of their dry weight, making them highly efficient for biofuel production [109]. In addition to biodiesel, microalgae can also be used to produce bioethanol through fermentation and biogas through anaerobic digestion. Moreover, certain microalgae species can produce hydrogen gas under specific conditions, offering potential as a clean and renewable energy source [118].

Zooming into South East Asia countries, the main microalgae players in biofuel production field are *Botryococcus braunii*, *Chlorella* sp., *Micractinium* sp., *Mychonastesrotundus* sp., *Nannochloropsis* sp., *Dunaliella* sp. and *Schizochytrium* sp. (Table 2). In this field of research, Indonesia, Malaysia and Thailand are the major contributors among all. These microalage are mainly sourced for their high lipid content. One interesting research among all others is the study of the detailed lipid content within the microalgae *Micractinium* such as myristic acid, palmitic acid, palmitoleic acid, hexadecadienoic acid, stearic acid, oleic acid, linoleic acid, and linolenic acid [39]. These biofuel researches sourced from microalgae is pivotal for the South East Asia economy as this is a potential high return on investment project that are essential for developing countries to elevate their economic capabilities to greater heights with minimal capital investments.

Table 2: Known / Recent microalgae biofuels applications / products in South East Asia region.

No.	Species	Component / Characteristics	Extraction techniques; Application / Product	Company / Country	References
1	*Botryococcus (braunii, braunii KMITL 2)*	Hydrocarbon, lipid	Soxhlet extraction (n-hexane); Biodiesel, high oil productivity	Malaysia, Thailand	[21], [30], [33], [47]
2	*Carteria (sp. AARL G045, sp. AARL G046)*	Lipid	Soxhlet extraction (n-hexane); Bio-oil	Thailand	[46]
3	*Chaetoceros*	Carotenoids, chlorophyll, lipid, protein, xanthophyll	Flow cytometric cell sorting; Biodiesel, biofuel	Philippines, Singapore	[15], [35]
4	*Chlamydomonas (sp., sp. UKM 6)*	Lipid	Soxhlet extraction (methanol:chloroform (2:1)); Biodiesel, bio jet fuel	Malaysia	[23], [24]
5	*Chlorella (sorokiniana, sp., sp. AARL G008, spp., spp. UKM 8, vulgaris, vulgaris mutant)*	Carotenoids, cellulose, chlorophyll, ethanol, fatty acids, glycerol, lipid, omega-3 fatty acids, pigment, polyunsaturated fatty acids, protein, starch, xanthophyll	Binary solvent extraction; Biodiesel, bioethanol, biofuel, bio jet fuel, bio-oil, energy nexus, high oil productivity	Brunei, Indonesia, Malaysia, Philippines, Thailand	[7], [15], [18], [21], [22], [23], [24], [25], [28], [32], [38], [42], [46], [47], [48]
6	*Chlorococcum (sp.)*	Lipid	Soxhlet extraction (methanol:chloroform (2:1)); Biodiesel, bio jet fuel	Indonesia, Malaysia	[9], [23]
7	*Choricystis (parasitica)*	Lipid	Soxhlet extraction (methanol:sulfuric acid (6:1) and chloroform (1:1));	Indonesia	[39]

			Biodiesel		
8	*Cochlodinium (sp.)*	Lipid	(N/A); Biofuel	Malaysia	[26], [43]
9	*Crypthecodinium (cohnii)*	Lipid	(N/A); Biodiesel, high oil productivity	Malaysia	[21], [47]
10	*Cylindrotheca (spp.)*	Lipid	(N/A); Biodiesel, high oil productivity	Malaysia	[21], [47]
11	*Dunaliella (primolecta, sp. KU12, sp. KU24, sp. KU30, sp. KU32)*	Biomass, lipid	Soxhlet extraction (methanol, water, chloroform); Biodiesel, high oil productivity	Malaysia, Thailand	[21], [45], [47]
12	*Glagah microalgae*	Fatty acids	Extracted via 5 stages: harvesting, weaving, methylation, extraction and washing; Biodiesel	Indonesia	[41]
13	*Haematoccocus*	Carotenoids, chlorophyll, lipid, protein, xanthophyll	Soxhlet extraction (hexane:methanol (3:1); Biodiesel, biofuel	Philippines, Singapore	[15], [29]
14	*Hydrodictyon (reticulatum)*	Lipid	(N/A); Bioethanol	Myanmar	[27]
15	*Isochysis (spp.)*	Lipid	(N/A); Biodiesel, high oil productivity	Malaysia	[21], [47]
16	*Micractinium (conductrix, sp.)*	Hexadecadienoic acid, linoleic acid, linolenic acid, lipid, myristic acid, oleic acid, palmitic acid, palmitoleic acid, stearic acid	Soxhlet extraction (methanol:sulfuric acid (6:1) and chloroform (1:1)); Biodiesel	Indonesia, Malaysia	[31], [39]

17	*Monallanthussalina (N)*	Lipid	(N/A); Biodiesel, high oil productivity	Malaysia	[21], [47]
18	*Monoraphidium (sp., sp. AARL G044)*	Lipid	Soxhlet extraction (methanol:sulfuric acid (6:1) and chloroform (1:1)); Biodiesel, bio-oil	Indonesia, Thailand	[39], [46]
19	*Mychonastesrotundus (sp.)*	Hexadecadienoic acid, linoleic acid, linolenic acid, myristic acid, oleic acid, palmitic acid, palmitoleic acid, stearic acid	Soxhlet extraction (methanol:sulfuric acid (6:1) and chloroform (1:1)); Biodiesel	Malaysia	[31]
20	*Nannochloris (spp.)*	Lipid	(N/A); Biodiesel, high oil productivity	Malaysia	[21], [47]
21	*Nannochloropsis (oculata, spp.)*	Lipid	(N/A); Biodiesel, biofuel, high oil productivity	Indonesia, Malaysia, Singapore	[21], [35], [40], [47]
22	*Neochloris (oleoabundans)*	Lipid	(N/A); Biodiesel, high oil productivity	Malaysia	[21], [47]
23	*Nitzschia (spp.)*	Lipid	(N/A);Biodiesel, high oil productivity	Malaysia	[21], [47]
24	*Nostoc (HS-20)*	Fatty acids	Extracted via 5 stages: harvesting, weaving, methylation, extraction and washing; Biodiesel	Indonesia	[41]
25	*Phaeodactylum (tricornulum)*	Lipid	(N/A); Biodiesel, high oil productivity	Malaysia	[21], [47]

26	*Scenedesmus (sp. AARL G022)*	Lipid	Soxhlet extraction (hexane); Bio-oil	Thailand	[46]
27	*Schizochytrium (mangrovei PQ6, spp.)*	Lipid, polyunsaturated fatty acids, squalene	Soxhlet extraction (methanol, water, chloroform); Biodiesel, high oil productivity	Malaysia, Vietnam	[21], [44], [47]
28	*Skeletonema (costatum)*	Lipid	Flow cytometric cell sorting; Biodiesel	Singapore	[35]
29	*Spirogyra (sp.)*	Lipid, protein	(N/A); Biodiesel	Indonesia, Malaysia	[34], [37]
30	*Spirulina (platensis, sp.)*	Carbohydrate, carotenoids, chlorophyll, fatty acids, lipid, protein, xanthophyll	Soxhlet extraction (hexane:methanol (3:1); Biodiesel, biofuel	Indonesia, Philippines	[15], [36], [41]
31	*Stigonematales (sp.)*	30.30% C, 40.87% O	(N/A); Bioenergy, biofuel	Brunei	[19], [20]
32	*Streptomyces (thermocarboxydus)*	Lipid	(N/A); Biodiesel	Thailand	[22]
33	*Synechococcus (sp. HS-9)*	Fatty acids	Extracted via 5 stages: harvesting, weaving, methylation, extraction and washing; Biodiesel	Indonesia	[41]
34	*Tetraselmis (sueica)*	Lipid	(N/A); Biodiesel, high oil productivity	Malaysia	[21], [47]
35	*Tetraspora (sp.)*	Lipid, protein	(N/A); Biodiesel	Indonesia, Malaysia	[34], [37]

36	*Thalassiosira*	Lipid	Flow cytometric cell sorting; Biodiesel	Singapore	[35]

4. Pharmaceuticals and Cosmetics

The microalgae is one of the major players and ingredients in the cosmetic industry, supporting a exponentially growing business volume of up to $580 billion dollars by the year 2027 [114]. Microalgae are a rich source of bioactive compounds with potential applications in the pharmaceutical and cosmetics industries. Many microalgae produce secondary metabolites, such as polysaccharides, peptides, and pigments, that exhibit a wide range of biological activities. For instance, some microalgae produce compounds with anti-aging, antioxidant, anti-inflammatory, phycoimmunomodulatory, antimicrobial, and anticancer properties, making them valuable for developing new pharmaceutical agents [128].

Recent innovations in microalgae research have introduced microalgae-based nanocarriers as a promising tool for targeted drug delivery, enhancing the bioavailability and controlled release of therapeutic compounds [114]. These natural, biocompatible carriers offer a sustainable alternative to synthetic materials in nanomedicine. Additionally, emerging trends highlight the integration of microalgae in advanced fields such as personalized nutrition, reflecting their expanding role beyond traditional medicine and food applications. The nanomaterials not only enhances the biomass and product yields, but also improves the stress tolerance and nutrient uptake during microalgae cultivation [114]. They have also provide cost-effective extraction, nano-induced flotation, flocculation and sedimentation that stremlined the entire microalgae cultivation and harvesting processes. These developments underscore microalgae's growing potential in addressing global challenges through green and cutting-edge technologies [128].

In the cosmetics industry, microalgae are prized for their skin-enhancing properties. Algal extracts, such as those from *Dunaliella salina*, are rich in beta-carotene and other carotenoids, which are known for their antioxidant activity [148]. These compounds help protect the skin from oxidative stress and UV-induced damage, thus preventing premature aging. Additionally, microalgae like *Chlorella* are used for their moisturizing and detoxifying properties, as they can promote collagen production and improve skin elasticity [146]. Microalgae are also explored for wound healing applications, as some species produce exopolysaccharides with skin regenerative properties. The growing interest in natural and sustainable ingredients in the cosmetics industry has further propelled the use of microalgae, making them a popular choice for clean beauty products [119].

The South East Asia countries are also active players in the microalgal pharmaceutical and cosmetic industries. Some of the most popular candidates selected for pharmaceutical and cosmetic raw source are *Chlorella* sp., *Spirulina* sp., *Scenedesmus* sp., *Aurantiochytrium* and *Micractinium* (Table 3). Indonesia is the major contributor to this field of microalagal research, followed by Vietnam and Malaysia. The bioactive compounds, triazine derivatives, pyridine derivatives, acridine derivatives, anticancer compounds sourced naturally from these microalgae are vital supporting agents to the pharmaceutical and healthcare industry within this region. Interestingly, the docohexanoic sourced from *Aurantiochytrium* is capable of preventing neural and cardiovascular diseases as well as maintaining normal brain function.

Table 3: Known / Recent microalgae pharmaceutical and cosmetic applications / products in South East Asia region.

No.	Species	Component / Characteristics	Extraction techniques; Application / Product	Company / Country	References
1	*Amphiprora (alata VACC-007)*	Anticancer compounds	Soxhlet extraction (methanol:chloroform (1:1); Potential anticancer drugs	Vietnam	[57]
2	*Ankistrodesmus (gracilis VACC-010, stipitatus)*	Anticancer compounds, nutraceuticals	Soxhlet extraction (methanol:chloroform (1:1); Next generation food, next generation fuel, next generation nutraceuticals, potential anticancer drugs	Singapore, Vietnam	[50], [57]
3	*Aurantiochytrium (sp., sp. SC145)*	Carbohydrates, carotenoid, docohexanoic acid, fatty acids, lipid, protein	Soxhlet extraction (methanol); Antioxidation properties, cardio-protection, neuroprotection, used in cosmetics, used in medicines, visual acuity	Indonesia, Vietnam	[12], [54], [58]
4	*Chaetoceros (calcitrans)*	Antioxidants, carotenoids, chlorophyll, lipid, omega-3 fatty acids, omega-6 fatty acids, protein, xanthophyll	Soxhlet extraction (acetone); Natural sources of antioxidants, potential for cosmetics, potential for pharmaceuticals	Malaysia, Philippines	[8], [15]
5	*Chlorella (ellipsoidea, sorokiniana, sp., vulgaris)*	Antioxidants, carotenoids, chlorophyll, immune stimulator compounds, lipid, minerals, nutraceuticals, omega-3 fatty acids, omega-6 fatty acids, polysaccharides, protein, vitamins, xanthophyll	Soxhlet extraction (methanol); Natural sources of antioxidants, next generation food, next generation fuel, next generation nutraceuticals, potential for cosmetics, potential for pharmaceuticals	Indonesia, Malaysia, Philippines, Singapore	[8], [13], [14], [15], [50]
6	*Chlorococcum (sp.)*	Lipid	Soxhlet extraction (dichloromethane:methanol (2:1)); Potential	Indonesia	[9]

			for cosmetics		
7	*Haematococcus*	Carotenoids, chlorophyll, lipid, protein, xanthophyll	Soxhlet extraction (acetone); Potential for cosmetics, potential for pharmaceuticals	Philippines	[15]
8	*Isochrysis (galbana)*	Antioxidants, omega-3 fatty acids, omega-6 fatty acids	Three antioxidant chemical assays (thiobarbituric acid, ferric thiocyanate and 1, 1'-diphenyl-2-picrylhydrazyl); Natural sources of antioxidants	Malaysia	[8]
9	*Micractinium (ehime IPOME-1, reisseri, sp. CCAP IPOME-2)*	Carotenoids, chlorophyll, nutraceuticals	Soxhlet extraction (methanol:chloroform (1:1); Bioactive compounds, next generation food, next generation fuel, next generation nutraceuticals	Indonesia, Singapore	[50], [51]
10	*Mychonastes (rotundus IPOME-3)*	Carotenoids, chlorophyll	Soxhlet extraction (methanol:chloroform (1:1); Bioactive compounds	Indonesia	[51]
11	*Nannochloropsis (oculata)*	Antioxidants, omega-3 fatty acids, omega-6 fatty acids	Three antioxidant chemical assays (thiobarbituric acid, ferric thiocyanate and 1, 1'-diphenyl-2-picrylhydrazyl); Natural sources of antioxidants	Malaysia	[8]
12	*Navicula (salinicola)*	Bioactive compounds	Soxhlet extraction (chloroform);Anti-inflammatory properties	Indonesia	[53]
13	*Oscillatoria (sp., sp. IPOME-4)*	Acridine derivatives, bioactive compounds, carotenoids, chlorophyll, fatty acids, pyridine derivatives, triazine derivatives	Soxhlet extraction (methanol:chloroform (1:1); Bioactive compounds, new natural antibiotics, new natural drug	Indonesia, Malaysia	[49], [51]
14	*Scenedesmus (bajacalifornicus,*	Antioxidants, nutraceuticals, omega-3 fatty acids, omega-6	Three antioxidant chemical assays (thiobarbituric acid, ferric thiocyanate and 1,	Malaysia, Singapore	[8], [50]

	pectinatus, quadricauda)	fatty acids	1'-diphenyl-2-picrylhydrazyl); Natural sources of antioxidants, next generation food, next generation fuel, next generation nutraceuticals		
15	*Spirulina (platensis, sp.)*	Antibacterial agent, bioactive compounds, carotenoids, chlorophyll, fatty acids, lipid, phycocyanin, protein, xanthophyll	Soxhlet extraction (acetone); Anti-bacterial soap, antioxidant properties, functional food, potential for cosmetics, potential for pharmaceuticals	Indonesia, Philippines	[15], [17], [52], [55], [56]
16	*Tetraselmis (tetrathele)*	Antioxidants, omega-3 fatty acids, omega-6 fatty acids	Three antioxidant chemical assays (thiobarbituric acid, ferric thiocyanate and 1, 1'-diphenyl-2-picrylhydrazyl);Natural sources of antioxidants	Malaysia	[8]
17	*Thraustochytrium (sp. TN22)*	Squalene	Soxhlet extraction (n-hexane); Antioxidant properties, cardio-protection, detoxifier, skin hydration	Vietnam	[59]

5. Aquaculture and Animal Feed

Microalgae are a techno-fundamental and nutritive component of aquaculture, serving as a primary food source for various aquatic species [125]. They provide essential nutrients, including proteins, lipids, vitamins, and minerals, which are crucial for the growth and development of fish, shrimp, mollusks, and other valuable aquaculture organisms that requires pricey and specific feeds such as the Javan and Malaysian mahseers, tilapia, rasbora, striped catfish, zebrafish, and koi carps [121, 123, 124]. Their high levels of protein, polyunsaturated fatty acids (PUFAs), antioxidants, vitamins, and minerals make them a valuable substitute for conventional feed sources like fishmeal and soybean meal. This also indirectly reduces the costs of research involving these aquatic species, as the material costs are relatively lower compared to commercial feeds [122]. For instance, microalgae like *Nannochloropsis* and *Isochrysis* are commonly used in hatcheries to feed larval stages of marine species, supporting their early development and enhancing survival rates [131]. However, despite their promise, large-scale adoption faces challenges. High production costs, limited scalability, variability in biomass quality, and the need for downstream processing (for example, cell wall disruption) are significant bottlenecks. Additionally, digestibility can be an issue in animals with less adapted gut microbiota, requiring further optimization of feed formulations.

In addition to direct feeding, microalgae play a role in enhancing the nutritional quality of live feeds such as rotifers and Artemia. By enriching these organisms with microalgae, they become a more nutritious food source for higher trophic levels in aquaculture systems [131]. This approach helps improve the health and growth rates of farmed species, leading to better yields. Microalgae are also used as a feed supplement for terrestrial animals, including livestock, poultry, pets and even non-human primates. They provide a sustainable and nutrient-dense alternative to conventional feed ingredients, offering benefits such as improved immunity, better feed conversion ratios, and enhanced animal health. The use of microalgae in animal feed can also contribute to the reduction of antibiotics, promoting a more sustainable and responsible approach to animal husbandry [130].

The use of microalgae in aquaculture and animal feed industry is not new to the South East Asia countries. The *Chlorella* sp. and *Spirulina* sp. are the most frequently utilized microalgae for animal feed (Table 4). They encompass all the essential nutrients such as protein, fatty acids, lipids, carotenoids, phophorus, nitrogen, bioactive compounds and antioxidants that are crucial for the growth of the animal and aquatic species. Malaysia, Indonesia and Philippines made the major contribution towards this field, focusing on reducing the costs of animal feed especially in aquaculture.

Table 4: Known / Recent microalgae aquaculture and animal feed applications / products in South East Asia region.

No.	Species	Component / Characteristics	Extraction techniques; Application / Product	Company / Country	References
1	*Ankinstrodesmus (sp.)*	Antioxidants, bioactive compounds, lipid, pigments, polysaccharides, protein, vitamins	(N/A); Animal feed	Malaysia	[60]
2	*Caulerpa (lentillifera)*	Bioactive compounds, minerals, polyunsaturated fatty acids, vitamins	(N/A); Enhances growth of sandfish and Babylon snail	Vietnam	[64], [65]
3	*Chaetoceros*	Arachidonic acid, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, protein	Flow cytometric cell sorting; Animal feed	Philippines	[15]
4	*Chlorella (sp., vulgaris TRG 4C)*	Antioxidants, arachidonic acid, bioactive compounds, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, fatty acids, gamma linolenic acid, immune stimulator compounds, lipid, minerals, nitrogen, phosphorus, pigments, polysaccharides, protein, trace metals, vitamins	Flow cytometric cell sorting; Animal feed, aquaculture industry, biofertilizer	Indonesia, Malaysia, Philippines	[13], [14], [15], [32], [60], [61]
5	*Desmodesmus (sp.)*	Oil, protein	Soxhlet extraction; Aquaculture sustainability, fisheries sustainability	Thailand	[62]
6	*Haematococcus*	Arachidonic acid, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, protein	Flow cytometric cell sorting; Animal feed	Philippines	[15]
7	*Isochrysis*	Docosahexanenoic acid	(N/A); Animal feed	Vietnam	[63]

	(galbana)				
8	*Nannochloropsis (oceanica)*	Nitrogen, phosphorus, trace metals	Natural extraction and autoclave; Aquaculture industry	Malaysia	[61]
9	*Pediastrum (spp.)*	Protein	Protein extraction kit; Animal feed	Thailand	[10]
10	*Scenedesmus (sp.)*	Antioxidants, bioactive compounds, lipid, pigments, polysaccharides, protein, vitamins	(N/A); Animal feed	Malaysia	[60]
11	*Spirogyra (sp.)*	Lipid, protein	(N/A); Animal feed, biofertilizer	Indonesia	[37]
12	*Spirulina*	Arachidonic acid, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, protein	Flow cytometric cell sorting; Animal feed	Philippines	[15]
13	*Tetraspora (sp.)*	Lipid, protein	(N/A); Animal feed, biofertilizer	Indonesia	[37]

6. Environmental Applications

Microalgae offer various environmental applications, particularly in biorefinery for wastewater treatment, microalgal biomass valorization, as well as industrial CO_2 carbon sequestration (Figure 3). In wastewater treatment, microalgae are employed for their ability to photosynthetically absorb CO_2 and utilize nutrients such as nitrogen and phosphorus to generate biomass [108]. These nutrients, often present in excess in wastewater, can lead to eutrophication in natural water bodies, causing algal blooms and depleting oxygen levels. By integrating microalgae in wastewater treatment systems, these nutrients can be efficiently removed, reducing pollution and promoting water quality [108]. The utilization of microalgal-bacterial energy nexus by [111] had further improved the CO_2 sequestration and remediation of wastewater pollutants. Microalgae-based systems, such as algal ponds and photobioreactors, are also used to treat industrial effluents, removing heavy metals and other contaminants. The biomass produced during this process can be harvested and utilized for various applications, including biofuel production and bioproducts, making the approach both environmentally and economically viable [111].

In the context of carbon sequestration, microalgae consortia have a high photosynthetic efficiency and can absorb large amounts of CO_2 from the atmosphere [143]. This capability positions microalgae as a potential tool for mitigating climate change by capturing and storing carbon dioxide. Furthermore, microalgae can be cultivated on non-arable land and in saline or wastewater, making them a versatile and sustainable option for carbon capture and utilization [143]. The captured carbon can be converted into valuable products, such as biofuels, bioplastics, and fertilizers, contributing to a circular economy [143]. It is believed that one tonne of microalgal biomass can fix around 1.8 tonnes of carbon dioxide during its entire growth cycle. In other words, microalgae generally is capable of removing approximately 1.83 kg of carbon dioxide per meter square per day under optimal cultivation conditions [143]. The recent pilot project such as the CHITOSE C4 from Sarawak has demonstrated the capability of microalgae to absorb carbon dioxide gas directly from power plant to support their growth. This initiative will not only facilitates the carbon dioxide reduction from the power plant and other manufacturing industries, but also channel these carbon dioxide to enhance the microalgae productivity to produce value-added products [143].

The utilization of microalgae in environmental remediation is an emerging industry in the South East Asia, with Malaysia and Indonesia being the leading contributors. A plethora of microalgae species were selected for this application, namely *Chlorococcum* sp., *Chlorella* sp., *Nannochloropsis* sp., *Botryococcus* sp. as well as *Spirulina* sp. (Table 5). Their capabilities in phycoremediation had made them the most feasible candidates in carbon footprint reduction and wastewater remediation. Their roles had not only contributed to greatly benefit the environment (by reducing greenhouse gas emissions) but also reducing costs of the waste management industry across the South East Asia countries.

Table 5: Known / Recent microalgae environmental remediation applications / products in South East Asia region.

No.	Species	Component / Characteristics	Extraction techniques; Application / Product	Company / Country	References
1	*Ankistrodesmus (augustus)*	Biomass	(N/A); Removal of pollutants, removal of 60% total nitrogen, ammonia and phosporus in wastewater treatment	Malaysia	[81]
2	*Arthrospira (platensis)*	Lipid, oil	Soxhlet extraction; Biodiesel	Indonesia	[77]
3	*Botrydiopsis (Arrhiza)*	Lipid	Soxhlet extraction (chloroform:methanol (2:1)); Biomass	Malaysia	[67]
4	*Botryococcus (braunii, sp.)*	Fatty acids, hydrophobic surface, lipid, oil	Soxhlet extraction; Biodiesel, removal of arsenic by 9%, wastewater treatment	Indonesia, Malaysia	[72], [73], [77]
5	*Chlamydomonas (sp.)*	Fatty acids, lipid	Soxhlet extraction (chloroform:methanol (2:1)); Wastewater treatment	Malaysia	[73]
6	*Chlorella (ellipsoidea, sorokiniana, sorokiniana CY-1, sp., vulgaris)*	Efficient photosynthesis, fatty acids, lipid, oil, pigments	Soxhlet extraction (chloroform:methanol (2:1)); Biodiesel, biomass, oil-based fuel reduce carbon emissions, removal of 80.37% arsenic, wastewater treatment	Indonesia, Malaysia, Singapore, Thailand	[7], [30], [32], [68], [70], [73], [74], [78], [82]
7	*Chlorococcum (aquaticum, humicola, sp.)*	Fatty acids, lipid, nitrogen, phosphorus	Soxhlet extraction (chloroform:methanol (2:1)); Biomass, removal of 99% zinc, wastewater treatment	Brunei, Malaysia	[66], [73], [81]
8	*Desmodesmus (sp.)*	Nitrogen, phosphorus	(N/A); Biomass	Brunei	[66]
9	*Haematococcus (pluvialis)*	Biomass	(N/A); Removal of 91.7% nitrogen and 100% phosphorus	Malaysia	[81]

10	*Isochrysis (sp.)*	Chlorophyll-A, fatty acids, lipid, phaeophytin	Soxhlet extraction (chloroform:methanol (2:1)); Biomass, reduce carbon emissions	Malaysia	[69], [71]
11	*Klebsormidium (flaccidum GN-2)*	Starch	Supercritical carbon dioxide extraction; Biomass	Malaysia	[3]
12	*Micractinium (sp.)*	Nitrogen, phosphorus	(N/A); Removal of 75.56% nitrogen	Brunei	[66]
13	*Nannochloropsis (oculata, oculata YG-2, sp.)*	Chlorophyll-A, fatty acids, lipid, oil, phaeophytin, starch	Soxhlet extraction; Biodiesel, biomass, oil-based fuel, reduce carbon emissions, reduce greenhouse gas emissions	Indonesia, Malaysia	[3], [69], [71], [75], [77], [78]
14	*Scenedesmus (sp.)*	Biomass, fatty acids, lipid, oil	Soxhlet extraction (chloroform:methanol (2:1)); Oil-based fuel, removal of pollutants, removal of 90% total nitrogen, ammonia and phosphorus in wastewater treatment	Indonesia, Malaysia	[73], [78], [81]
15	*Spirogyra (sp.)*	Lipid, protein	(N/A); Reduce greenhouse gas emission, removal of 93.2% arsenic	Indonesia	[37]
16	*Spirulina (platensis)*	Oxygen producer for oxygen reduction reaction at cathode, phytoremediation	(N/A); Biomass, phytoremediation of Cd^{2+}, phytoremediation of Cr^{3+}, phytoremediation of Cu^{2+}, phytoremediation of Pb^{2+}	Indonesia	[79], [80]
17	*Synechococcus (HS-9)*	Lipid	Soxhlet extraction; Biodiesel	Indonesia	[76]
18	*Tetraselmis (sp.)*	Chlorophyll-A, phaeophytin technique)	Soxhlet extraction; Reduce carbon emissions, removal of 97% nickel	Malaysia	[71]
19	*Tetraspora (sp.)*	Lipid, protein	(N/A); Reduce greenhouse gas emissions	Indonesia	[37]
20	*Thalassiosira*	Lipid	(N/A); Potential wastewater treatment,	Malaysia	[83]

	(weissflogii)		removal of 59.5% arsenic		

7. Bioplastics and Biomaterials

The production of bioplastics and biomaterials from microalgae is an emerging field with the potential to reduce reliance on fossil fuels and decrease plastic pollution. Microalgae produce polysaccharides, proteins, and lipids, which can be processed into biodegradable plastics and polysaccharides such as agar, carrageenan, and alginate [104]. These valuable biosynthesis products are deemed gems in various industries for their gelling and thickening properties [104]. Despite their potential, microalgae-based bioplastics still face significant challenges. High production costs, low PHA yield per biomass, and complex downstream processing remain major bottlenecks. Moreover, the mechanical and thermal properties of algae-derived plastics often fall short of those from conventional petroleum-based plastics, limiting large-scale commercial application. Lack of industrial-scale infrastructure and limited public awareness further slow market penetration.

Polyhydroxyalkanoates (PHAs) are a class of bioplastics that can be synthesized by certain microalgae species, namely *Nostoc muscorum*, *Spirulina subsalsa*, *Spirulina platensis* and *Synechococcus* sp. PHAs are biodegradable and have similar properties to conventional plastics, making them suitable for various applications, including packaging, agricultural films, and medical devices [107]. The production of PHAs from microalgae offers a sustainable alternative to petroleum-based plastics, as they are biodegradable and do not contribute to long-term environmental pollution [107]. In addition to bioplastics, microalgae can be used to produce biomaterials with unique properties. For instance, microalgae-derived pigments, such as chlorophyll and phycocyanin, can be used as natural colorants in textiles and cosmetics [129]. Microalgae can also be engineered to produce high-value compounds, such as bioactive peptides and antioxidants, which can be incorporated into functional biomaterials for medical and cosmetic applications [129].

The microalgal sourced bioplastic and biomaterial industry is equally popular in Thailand and Indonesia among all the other countries in the South East Asia. The *Spirulina* sp., *Chlorella* sp. *Oscillatoria* sp. and *Arthrospira* sp. are some of the excellent candidates as reservoirs of raw materials for the bioplastic and biomaterial synthesis (Table 6). These microalgae are useful for the production of edible bioplastic for food packaging, cosmetic packaging and pharmacy packaging. One outstanding ressearch utilized *Oscillatoria* sp. to facilitate adsorption of cobalt ion from aqueous solution which aid significantly in biomaterial manufacturing.

Table 6: Known / Recent microalgae bioplastic and biomaterials applications / products in South East Asia region.

No.	Species	Component / Characteristics (Extraction techniques)	Extraction techniques; Application / Product	Company / Country	References
1	*Arthrospira (platensis NBQN1, platensis NLNA2)*	Polyhydroxyalkanoates	Soxhlet extraction (cold methanol); Bioplastics	Vietnam	[87]
2	*Chlorella (salina, vulgaris)*	Carbohydrate, lipid, polysaccharides, protein	Soxhlet extraction (glycerol); Bioplastics, food packaging industry	Indonesia, Malaysia	[11], [89]
3	*Mesopodopsis (orientalis)*	Enhanced microplastic ingestion	(N/A); Ingestion of microplastic particles by mysids	Thailand	[86]
4	*Microcystis (aeruginosa DTB1)*	Polyhydroxyalkanoates	Soxhlet extraction (cold methanol);Bioplastics	Vietnam	[87]
5	*Navicula (sp.)*	Enhanced microplastic ingestion	(N/A); Ingestion of microplastic particles by mysids	Thailand	[86]
6	*Oscillatoria (sp.)*	Biomaterial, enhanced microplastic ingestion	(N/A); Adsorption of cobalt ions from aqueous solution, ingestion of microplastic particles by mysids	Indonesia, Thailand	[84], [86]
7	*Scenedesmus (armatus)*	Carbohydrate, lipid, protein	(N/A); Increase biochemical composition	Thailand	[85]
8	*Spirulina (Arthrospira spp., platensis, sp.)*	Carbohydrate, carotenoids, lipid, phycocyanin, polysaccharides, protein	Soxhlet extraction (glycerol); Cosmetic packaging industry, edible bioplastics, food packaging industry, pharmaceutical packaging industry	Indonesia, Malaysia, Thailand	[1], [11], [88]

8. Agriculture and Horticulture

Microalgae have significant potential in agriculture and horticulture, primarily as biofertilizers and biostimulants. They can drive plant growth via the improvement of the nutrient availability as well as contributing towards soil nutrient cycling. Algal biofertilizers contain essential nutrients, such as nitrogen, phosphorus, and potassium, as well as trace elements and growth-promoting hormones [137]. These nutrients enhance soil fertility and promote plant growth, improving crop yields and quality. Microalgae also improve soil structure and water retention, which can be particularly beneficial in arid and semi-arid regions [105]. However, several limitations impede their widespread adoption. Production costs remain high due to cultivation, harvesting, and drying processes. Inconsistent field performance, especially under varying environmental conditions, also limits farmer confidence. Additionally, large-scale production requires significant infrastructure and water resources, posing sustainability and logistical challenges.

The use of microalgae as biostimulants involves their application to plants to enhance nutrient uptake, improve stress tolerance, and stimulate growth. Algal extracts contain bioactive compounds, such as phytohormones, amino acids, and polysaccharides, which can trigger physiological responses in plants [105,137]. These responses include enhanced root growth, increased chlorophyll production, and improved resistance to diseases and pests [105,137]. In addition to their uses as biofertilizers and biostimulants, microalgae can be employed as biopesticides. Some microalgae produce natural toxins that can deter or kill pests and pathogens, offering a sustainable alternative to synthetic pesticides [133]. The use of microalgae-based biopesticides can reduce the environmental impact of chemical pesticides and promote more sustainable agricultural practices [133]. Overall, microalgae offer a versatile and eco-friendly solution for improving agricultural productivity and sustainability.

Malaysia is the stellar pioneer in microalgae agriculture applications across other countries housed within the South East Asia region. *Spirulina* sp., *Chlorella* sp., *Haematococcus* sp., *Chaetoceros* sp. and *Nannochloropsis* sp. provides indispensable nutrients such as a-linolenic acid, palmitic acid, linoleic acid, oleic acid, undecylenic acid, docosahexaenoic acid, eicosapentaenoic acid, arachidonic acid and gamma linolenic acid to the agriculture crops for growth improvement and elevation (Table 7). These microalgae can act as fertilizers to rice fields, leafy vegetative plants and flowers. The main goal of this industry is to transform the existing traditional agriculture to algal agriculture without polluting the environment as well as creating a symbiotic relationship and healthy nutrient cycling ecosystem in a natural manner.

Table 7: Known / Recent microalgae agriculture applications / products in South East Asia region.

No.	Species	Component / Characteristics (Extraction techniques)	Extraction techniques; Application / Product	Company / Country	References
1	*Brachionus (plicatilis)*	Carbohydrate, fatty acids, lipid, protein	Soxhlet extraction (methanolic hydrochloric acid (5%, v/v)); Feed fish in aquaculture industry	Malaysia	[92], [93]
2	*Chaetoceros*	Arachidonic acid, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, protein	Soxhlet extraction (acetone); Biological components necessary for agriculture	Philippines	[15], [96]
3	*Chlorella (sp.)*	Arachidonic acid, carbohydrate, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, fatty acids, gamma linolenic acid, lipid, protein	Soxhlet extraction (acetone); Biological components necessary for agriculture, feed fish in aquaculture industry	Malaysia, Philippines	[15], [92], [93], [96]
4	*Dunaliella (salina KU 11)*	Beta-carotene, biomass	(N/A); Algal biotechnology to replace traditional agriculture	Thailand	[94]
5	*Haematococcus*	Arachidonic acid, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, protein	Soxhlet extraction (acetone); Biological components necessary for agriculture	Philippines	[15], [96]
6	*Isochrysis (sp.)*	Carbohydrate, fatty acids, lipid, protein	Soxhlet extraction (methanolic hydrochloric acid (5%, v/v)); Feed fish in aquaculture industry	Malaysia	[92], [93]
7	*Mixed microalgae*	Alpha-linolenic acid, linoleic acid, oleic acid, palmitic acid, undecylenic acid	(N/A); Healthy food source, renewable energy source	Malaysia	[91]
8	*Nannochloris (sp.)*	Carbohydrate, fatty acids, lipid, protein	Soxhlet extraction (methanolic hydrochloric acid (5%, v/v)); Feed	Malaysia	[92], [93]

			fish in aquaculture industry		
9	*Nannochloropsis (sp.)*	Carbohydrate, fatty acids, lipid, polysaccharides, protein	Soxhlet extraction (methanolic hydrochloric acid (5%, v/v)); Feed fish in aquaculture industry	Malaysia	[90], [92], [93]
10	*Nostoc*	Bio-fixation of carbon dioxide, nitrogen-fixation	(N/A); Fertilize rice fields, irrigate rice fields	Vietnam	[95]
11	*Spirulina (platensis)*	Arachidonic acid, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, protein	Soxhlet extraction (acetone); Bio-fertilizers, biological components necessary for agriculture	Philippines, Singapore	[15], [96], [97]
12	*Tetraselmis (sp.)*	Carbohydrate, fatty acids, lipid, protein	Soxhlet extraction (methanolic hydrochloric acid (5%, v/v)); Feed fish in aquaculture industry	Malaysia	[92], [93]

9. Research and Biotechnology

Microalgae serve as valuable model organisms in scientific research, particularly in the fields of photosynthesis, cell biology, and metabolic engineering. Their simple structure and fast growth rates make them ideal for studying fundamental biological processes. For instance, the green alga *Chlamydomonas reinhardtii* is extensively used as a model organism to study photosynthesis and chloroplast function, providing insights into the mechanisms of light energy conversion and carbon fixation [134]. This provides us with the knowledge on how the Ca^{2+} signalling machinery has evolved over time and also how microalgae can perceive and respond to environmental stimuli [134]. Despite their vast potential, several challenges persist. Genetic manipulation of many microalgal species remains difficult due to species-specific transformation barriers and limited availability of stable expression systems. Moreover, scalability of engineered strains for industrial applications is still limited by high production costs, inefficient harvesting techniques, and strain instability under outdoor conditions.

In biotechnology, microalgae are harnessed for the production of a wide range of high-value compounds, including recombinant proteins, enzymes, and pharmaceuticals. Through genetic engineering, microalgae can be modified to express foreign genes, enabling the production of complex proteins and bioactive molecules [110]. This approach is particularly valuable for producing therapeutic proteins, such as antibodies, vaccines, and hormones, in a cost-effective and scalable manner [110]. Microalgae are also used in synthetic biology to develop new metabolic pathways and biosynthetic processes. For example, researchers can engineer microalgae to further improve the production rate and yield of biofuels, such as hydrogen, ethanol, and biodiesel, by optimizing the metabolic pathways involved in lipid and carbohydrate metabolism. Surprisingly, the high lipid synthesis rate per hectare yield of the microalgae is seven to 31 times higher compared to that of other commercial oil corps [142]. This genetic manipulation extends to the production of industrial enzymes, which can be used in various applications, including food processing, textile production, and waste treatment. Moreover, microalgae are employed in environmental biotechnology for bioremediation and biosensing [147]. They can be engineered to detect and degrade environmental pollutants, such as heavy metals, organic contaminants, and excess nutrients. The use of microalgae in biosensors allows for the monitoring of environmental conditions, including water quality and pollutant levels, providing valuable data for environmental management [147].

The microalgal biotechnology applications in the South East Asia region are dominated equally by three countries, namely Malaysia, Indonesia, Philippines and Singapore. Recent microalgal biotechnology research are skewed towards microalgae species such as the *Spirulina* sp., *Chlorella* sp., *Nannochloropsis* sp., *Scenedesmus* sp., and *Haematococcus* sp (Table 8). Their applications in various fields of biotechnology like photobioreactor, vaccine delivery system, bioprospecting, chemometric analyses and fuel cells are revolutionizing the traditional industry and creating novel microalgal applications that will benefit the global human community. One of the most interesting research under this field is the microalgae-microbial fuel cell system that have the ability to diminish the COD level and total dissolved solid to 60% and 82.83% respectively from cafeteria wastewater in Indonesia [79].

Table 8: Known / Recent biotechnology applications / products in South East Asia region.

No.	Species	Component / Characteristics (Extraction techniques)	Extraction techniques; Application / Product	Company / Country	References
1	*Amphora (coffeiformis)*	Eicosapentenoic acid	(N/A); Evaluation of ammonium tolerance and lipid production through bioprospecting	Malaysia	[83]
2	*Botryococcus (braunii, sp.)*	Lipid, phytoremediation	(N/A); Assimilate high amount of carbon dioxide, bioremediation of bathroom greywater, lipid production for biodiesel	Malaysia	[99], [103]
3	*Chaetoceros*	Arachidonic acid, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, protein	Soxhlet extraction (acetone); Contains biological compounds necessary for industrial and biotechnological purposes	Philippines	[15]
4	*Chlorella (sorokiniana, sp., vulgaris)*	Arachidonic acid, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, protein	Soxhlet extraction (acetone); Assimilate high amount of carbon dioxide, biomass production through column photobioreactor, contains biological compounds necessary for industrial and biotechnological purposes, lipid production for biodiesel	Malaysia, Philippines, Singapore	[15], [74], [103]
5	*Chromochloris (zofingiensis)*	Oil, protein	(N/A); Exposure to ultraviolet light to stimulate photosynthesis	Singapore	[102]
6	*Haematococcus (pluviali)*	Arachidonic acid, astaxanthin, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, protein	Soxhlet extraction (acetone); Contains biological compounds necessary for industrial and biotechnological purposes, development of microalgal biotechnology to create high-value products	Indonesia, Philippines	[15], [98]

7	*Nannochloropsis (sp.)*	Lipid, polysaccharides, protein	(N/A); Application of mid-infrared chemical imaging and multivariate chemometrics, transgenic microalgae as vaccine delivery system to aquatic organisms	Malaysia, Singapore	[90], [101]
8	*Oocystis (heteromucosa)*	Eicosapentenoic acid	(N/A); Evaluation of ammonium tolerance and lipid production through bioprospecting	Malaysia	[83]
9	*Scenedesmus (obliquus, sp.)*	Lipid	(N/A); Assimilate high amount of carbon dioxide, lipid production for biodiesel	Malaysia	[103]
10	*Spirulina (platensis)*	Arachidonic acid, carotenoids, docosahexaenoic acid, eicosapentaenoic acid, gamma linolenic acid, lipid, oxygen producer for oxygen reduction reaction at cathode, protein	Soxhlet extraction (acetone); Contains biological compounds necessary for industrial and biotechnological purposes, reduction of chemical oxygen demand and total dissolved solid of cafeteria wastewater through microalgae-microbial fuel cell system	Indonesia, Philippines	[15], [79]
11	*Synechococcus (HS-9)*	Lipid	Soxhlet extraction; Biomass and biodiesel production through transesterification	Indonesia	[76]
12	*Thalassiosira (weissflogii)*	Eicosapentenoic acid	(N/A); Evaluation of ammonium tolerance and lipid production through bioprospecting	Malaysia	[83]
13	*Thraustochytrids*	Carotenoids, docosahexaenoic acid, hydrolytic enzymes, polyunsaturated fatty acids, squalene	Soxhlet extraction; Biodiesel production, biotechnological application	Indonesia	[100]

10. Priorities, emerging trends and unique microalgae research across South East Asia

South East Asia is increasingly recognizing the potential of microalgae for addressing food security, sustainable energy, environmental management, and economic development. Given the region's rich biodiversity and favorable climate, several priorities and research directions have emerged. Most South East Asia countries like Malaysia and Singapore have set priorities to improve biomass energy generation within the next decade. Some of the notable emerging trends are Malaysia and Singapore lead in applying gene-editing and metabolic engineering for strain improvement and metabolite overproduction, Thailand and Indonesia explore algal-bacterial systems to enhance productivity and resilience as well as integrative platforms are being developed to simultaneously produce biofuels, bioplastics, and nutraceuticals from microalgal biomass. The development of groundbreaking microalgae research and applications across South East Asia countries is growing exponentially recently, as summarized in Table 9. [138] isolated Antartic *Chlorella* sp. and further charaterized them. Interestingly, they discovered that these species can thrive at temperature up to 30 degree Celcius and in addition they encompass valuable fatty acids such as omega-3 poly unsaturated fatty acids (PUFAs). The algae cake, which is a by-product of the oil extraction, is utilized by the Nanyang Technological University microalgae research team to be processed into supplements and raw materials for food production in 2023. In the Sarawak state of Malaysia, a world's largest mass microalgae biomass production plant has been established in 2023 [140].

Interestingly, a recent survey conducted by an Indonesian research team revealed that majority of the Indonesian community are willing to try new microalgae-based food [144]. [135] examined the potential of 47 strains of cyanobacteria and microalgae species and they have successfully identified potential candidates for the production of polyhydroxyalkanoates as an indispensable source for bioplastic synthesis in Vietnam. [126] discovered that both *Tisochrysis lutea* and *Isochrysis galbana* are capable of producing the highest lipid and fatty acids content among all other microalgae species tested for the development of shrimp feed in Vietnam. Thailand native strains from species such as *Chlorella* sp., *Carteria* sp., *Scenedesmus* sp. and *Monorapbidium* sp. were some of the potential candidates for bio-oil production [115]. Recently, [141] has successfully developed a microalgae cultivation automated system for *Chlorella ellipsoidea* that requires less manpower to operate. The collaboration between Malaysia and Brunei research team discovered that *Scenedesmus obliquus* can speed up the sedimentation rate as it is one of the most auto-fluocculant microalgae [136]. The Philippines microalgae research team had characterised several marine microalgae such as *Amphora, Biddulphia* and *Campylodiscus* [127]. In Myanmar, water quality survey for microalgae species was performed in Mandalay Main Canal and they discovered several microalgae species such as *Cyanophyceae, Euglenophyceae, Chlorophyceae and Bacillariophyceae* [117].

11. Future perspectives, policy directions, technological roadmaps and the role of automation and AI in future microalgae research

South East Asia has favorable climatic conditions, rich biodiversity, and increasing demand for sustainable energy, making it ideal for large-scale microalgae biofuel development. Countries like Malaysia, Indonesia, Thailand, and Vietnam are exploring microalgae for biodiesel, bioethanol, and biohydrogen, particularly by utilizing CO_2 from industrial emissions and agricultural wastewater. The integration of microalgae into circular bioeconomy models is expected to improve both environmental and economic sustainability. To unlock this potential, South East Asian nations are gradually integrating green energy policies with support for renewable energy targets. For instance, Malaysia targets a 31% and 40% renewable energy generation by 2025 and 2035 goal [140]. The Malaysian government also pledged to build up 18.4 GW of renewable energy capacity by the year 2040 [140]. Several Southeast Asia countries like Singapore and Malaysia are allocating huge funding in microalgae research and development endeavors and public-private partnerships. More land and water use regulations are being planned for microalgal cultivation in the years to come. The Sarawak state government is collaborating with CHITOSE C4 from Japan to provide incentives for carbon-neutral and climate-resilient technologies. Cross-border collaboration such as under ASEAN Plan of Action for Energy Cooperation (APAEC), is also promoting regional harmonization of biofuel standards and research sharing [140].

The technological roadmaps of microalgae cultivation across South East Asia countries involves short-, mid- and long-term plannings. In short-term roadmap (1-3 years), identification of high-lipid microalgae strains native to tropical regions is crucial as a good headstart. Then, pilot-scale photobioreactors will be established to scale up the cultivation. Next, the integration with wastewater treatment plants will aid in prototype testing of this system. During the mid-term roadmap (3-7 years), large-scale outdoor cultivation systems can be established. Microalgal biorefineries that are capable of co-producing both biofuel and high-value bioproducts will be built. Besides, carbon dioxide capture system will be installed at all power plants and cement industries so that these carbon dioxide can be utilized for the microalgal biorefineries. During the long-term roadmap (7-15 years), full commercialization with government-backed subsidies will be implemented. Furthermore, the national and regional microalgal fuel networks will be established. The scale established enables for the export of biofuel and bio-based products globally.

Ultimately, the future of microalgae cultivation would shift towards fully automated system monitored by artificial intelligence as reviewed by [149] from Germany, whereby machine learning is utilized to completely monitor microalgae growth parameters such as biomass, pH, temperature, nutrients and metabolite level in an automated manner (Figure 4). This approach will not only reduce the production and operational costs, but also improve efficiency and productivity. As the microalgae research across South East Asia progress, it is crucial to ensure that the future direction is targeting towards benefiting the people in this region in terms of food security, biofuel availability, pharmaceutical as well as bioremediation.

12. Conclusion

In conclusion, microalgae represent a remarkable and versatile group of organisms with significant potential across a range of industries. Their ability to produce a variety of high-value compounds, including proteins, lipids, and bioactive molecules, positions them as a sustainable resource for food, pharmaceuticals, cosmetics, and biofuels. The rapid growth rates and adaptability of microalgae, coupled with their capability to thrive in diverse environments, offer promising avenues for renewable energy production and environmental management, such as carbon sequestration and wastewater treatment.

Moreover, the increasing interest in natural and sustainable products aligns with the potential of microalgae to provide eco-friendly alternatives to conventional materials and processes. As research and technological advancements continue, the applications of microalgae are expected to expand, contributing to solutions for some of the most pressing global challenges, including climate change, food security, and environmental degradation. The ongoing exploration and innovation in the cultivation and utilization of microalgae underscore their importance in the development of a more sustainable and resilient future. As such, microalgae stand as a key player in the growing bioeconomy, offering a path toward a greener and more sustainable world.

Acknowledgement

This work is fully funded by the PETRONAS Research Sdn. Bhd. through the PETRONAS-Academia Collaboration Dialogue 2023 Grant (IRG/F07/PRSB/86460/2024) awarded to Chung H.H..

Table 9. The summary of recent groundbreaking microalgae research and applications across South East Asia. PUFAs: poly unsaturated fatty acids.

No.	Species	Algae Component (Extraction techniques)	Application/ Research	Country/ University	References
1	Antartic *Chlorella* sp.	Whole (Isolated using Bold Basal Media)	Research: this species can grow at temperature up to 30 degree Celcius and they are rich in valuable fatty acids such as omega-3 PUFAs	International Islamic University of Malaysia, Malaysia & Universiti Islam Sultan Sharif Ali, Brunei	[138]
2	*Chromochloris zofingiensis*	Algae cake, as known as by-product of the oil extraction (N/A)	Research: Algae cake can be converted into supplements and utilized in food production	Nanyang Technological University, Singapore	[132]
3	Microalgae	Microalgae biomass production plant (N/A)	Application: World's largest mass microalgae biomass production plant opened in Malaysia	Malaysian state of Sarawak and Chitose Carbon Capture Central (C4)	[140]
4	Microalgae	Food (N/A)	Application: Majority of the Indonesian community willing to try new microalgae-based food	University of Brawijaya, Indonesia	[144]
5	47 strains of microalgae and cyanobacteria	Whole (Soxhlet extraction (cold	Application: to produce polyhydroxyalkanoates (PHAs) as a source of	Vietnam Academy of Science and Technology	[135]

		methanol))	bioplastics	, Vietnam & Hanoi University of Pharmacy, Vietnam	
6	*Tisochrysis lutea* & *Isochrysis galbana*	Shrimp feed (Soxhlet extraction (dichloromethane-methanol-water))	Application: These species have the highest lipid and fatty acid content for shrimp aquaculture	Nha Trang University, Vietnam	[126]
7	Thailand native strains: *Chlorella* sp., *Carteria* sp., *Scenedesmus* sp. & *Monorapbidium* sp.	Lipid (Soxhlet extraction (hexane))	Application: Bio-oil production in Thailand	Chiang Mai University, Thailand	[115]
8	*Chlorella ellipsoidea*	Whole (N/A)	Application: microalgae cultivation automated system	Nakhon Si Thammarat Rajabhat University, Thailand	[141]
9	*Scenedesmus obliquus*	Whole (N/A)	Application: This auto-flocculant microalgae can speed up sedimentation rate	Universiti Brunei Darussalam, Brunei & Universiti Teknologi PETRONAS, Malaysia	[136]
10	*Spirulina* sp.	Whole (N/A)	Application: *Spirulina* sp. was used to improve childhood anemia and wight gain among Cambodia children	Institut Pasteur du Cambodge, Cambodia	[106]
11	*Amphora*, *Biddulphia* &	Whole (N/A)	Research: This is the early studies of	University of the	[127]

	Campylodiscus		marine microalgae in the Philippines	Philippines Los Banos, Philippines	
12	*Cyanophyceae, Euglenophyceae, Chlorophyceae & Bacillariophyceae*	Whole (N/A)	Research: Water quality survey for microalgae species conducted in Mandalay Main Canal, Myanmar	Pyay University, Myanmar & University of Myltkyina, Myanmar	[117]

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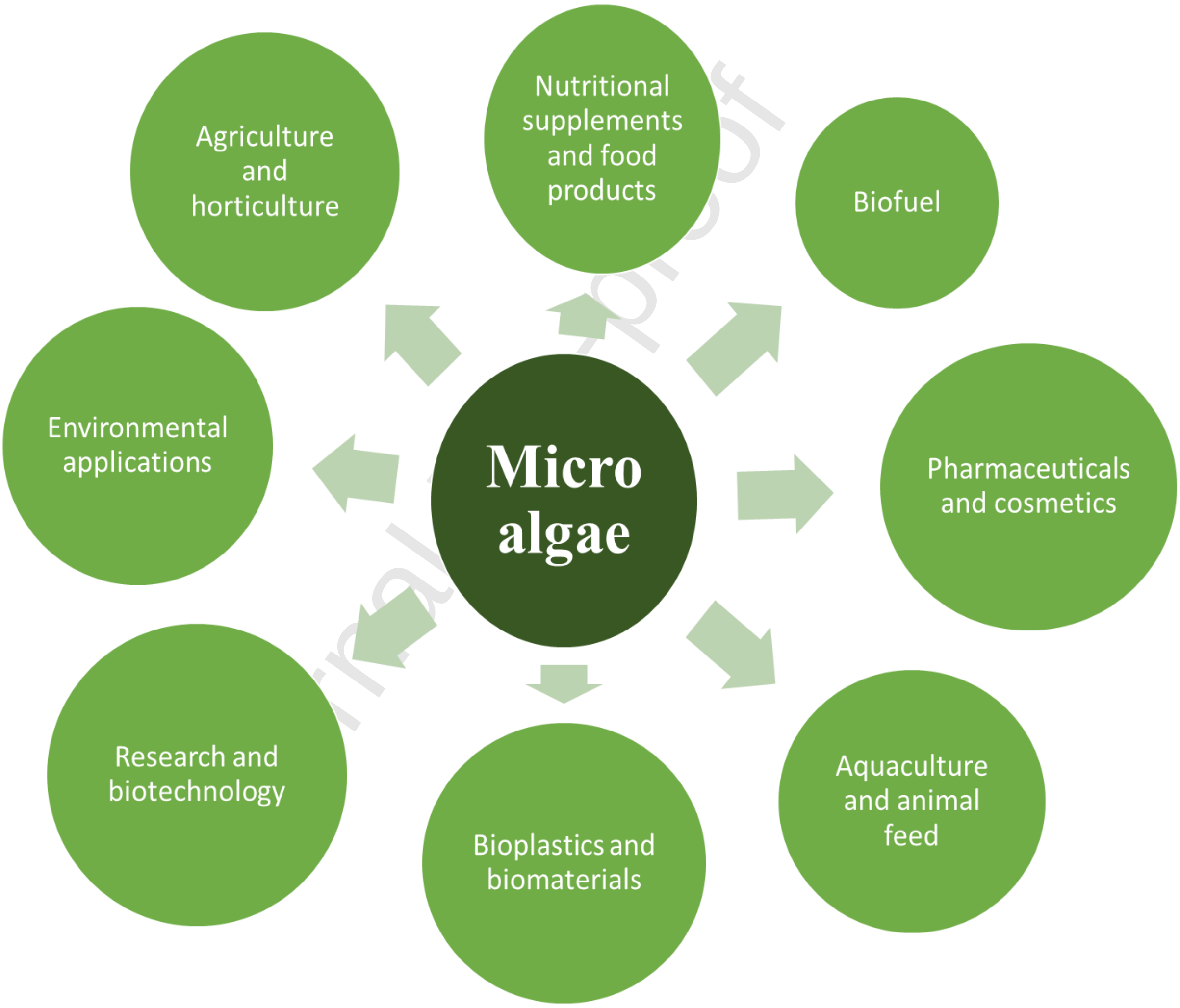


Figure 1. The summary of microalgae applications across the globe.

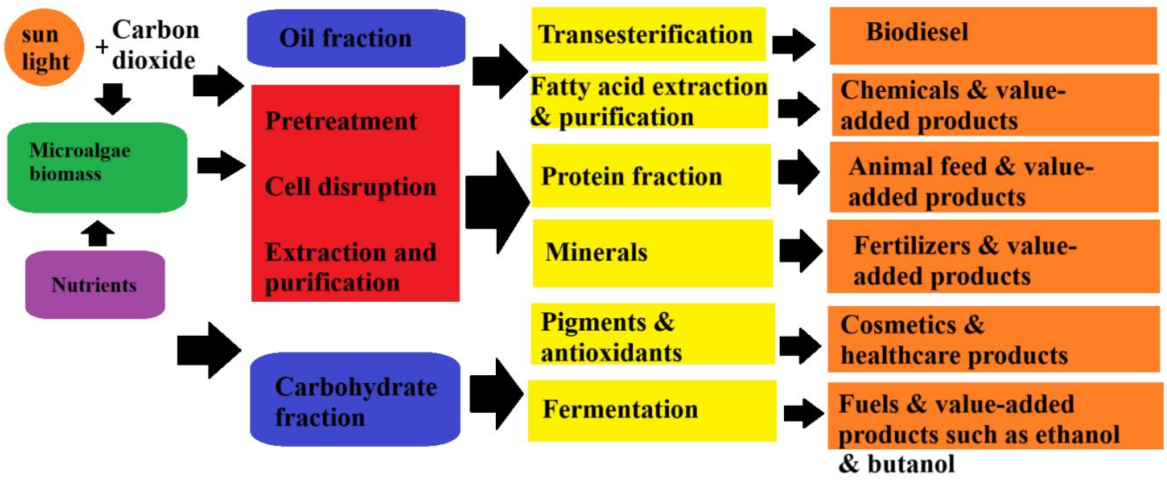


Figure 2. The overview of potential microalgae biorefinery bioproducts.

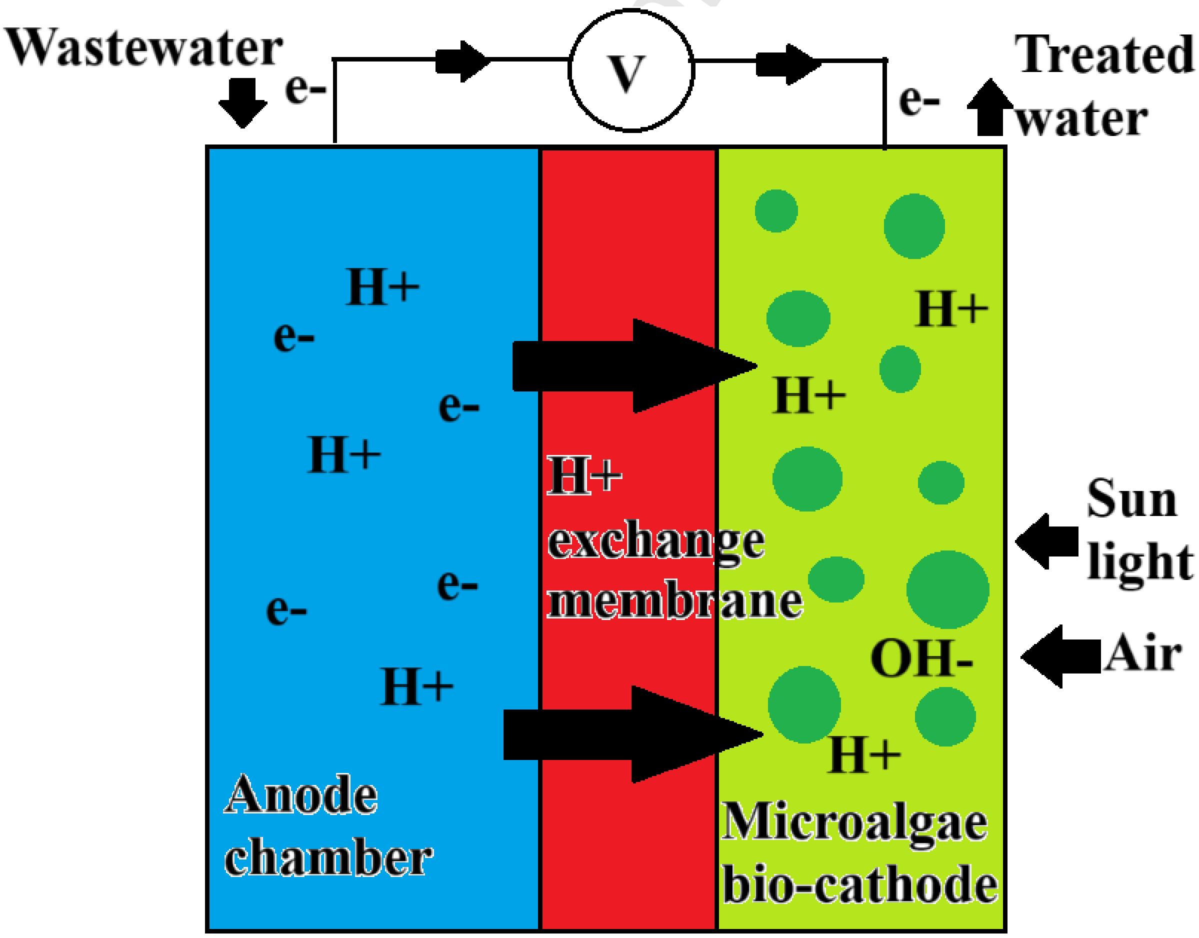


Figure 3. The microalgae fuel cell system to convert wastewater to treated water.

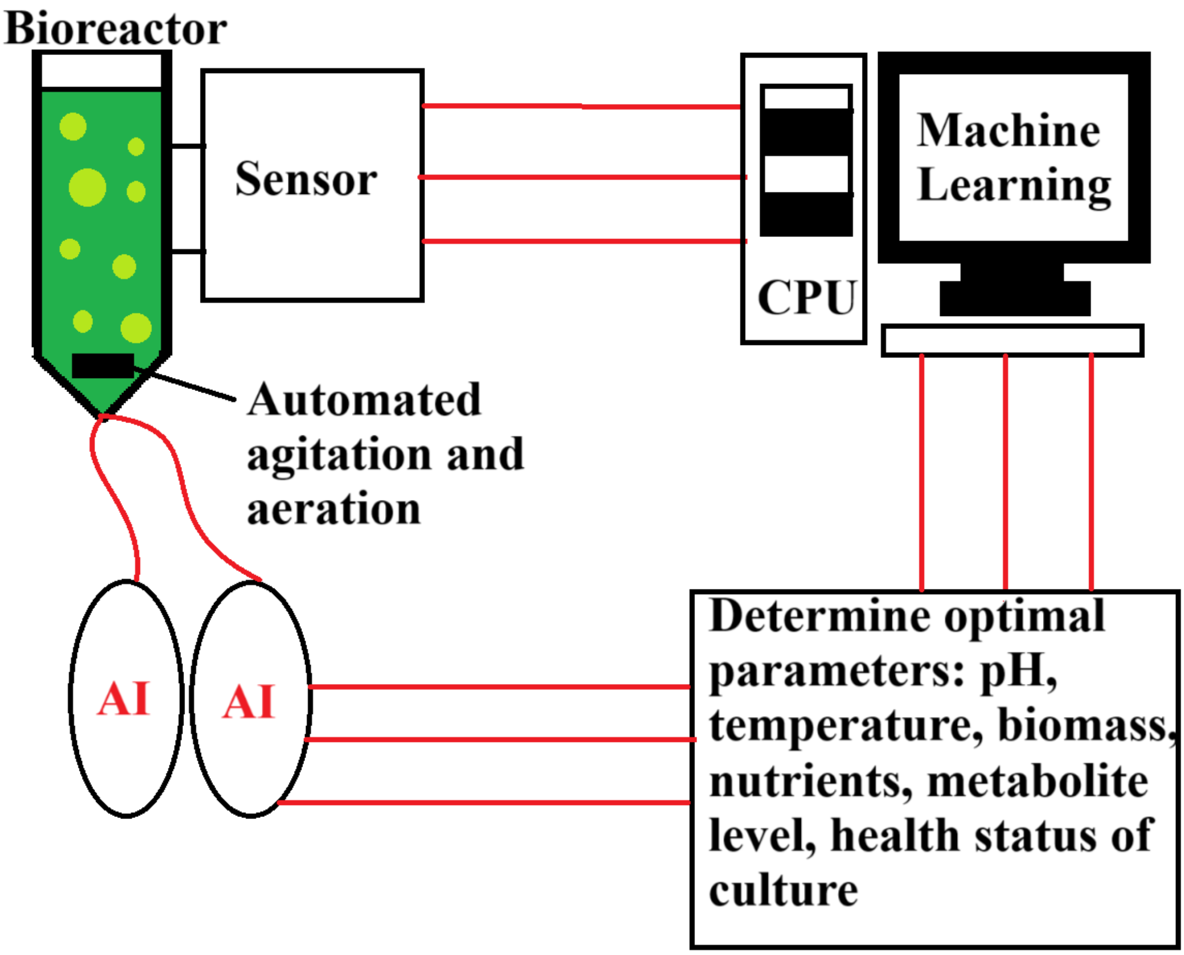
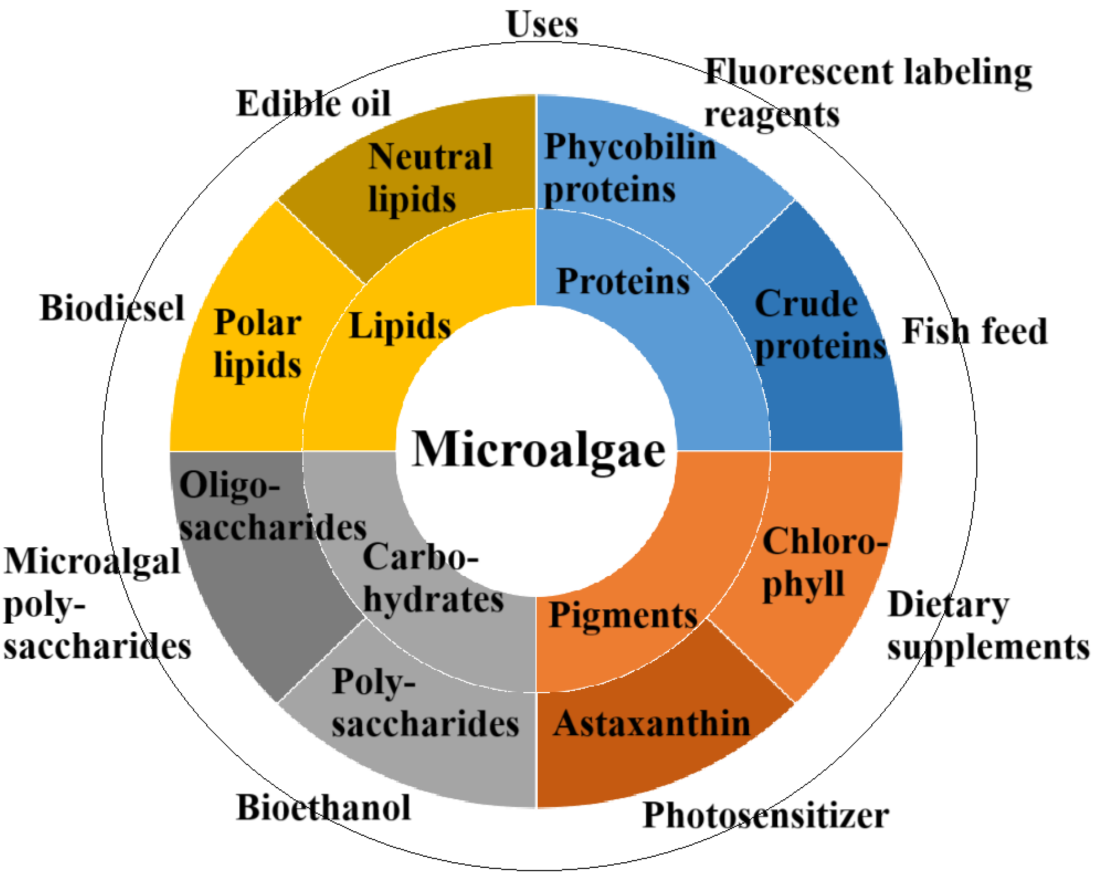


Figure 4. Fully automated microalgae cultivation system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



Graphical abstract

Highlights

- Microalgae thrive in freshwater and marine waters.
- Microalgae has vast applications.
- Microalgae applications across the Southeast Asia countries discussed.