Bioresource Technology 351 (2022) 127038

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Research trends and market opportunities of microalgal biorefinery technologies from circular bioeconomy perspectives

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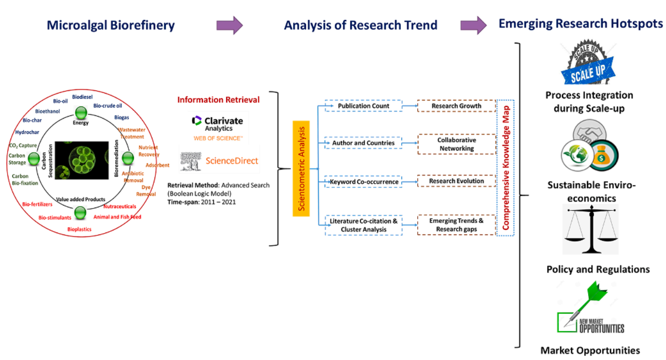
HIGHLIGHTS

- Research trends and future prospects of microalgal biorefinery was explored.
- Integrated zero-waste microalgal biorefinery are major identified research hotspots.
- Microalgae based products have enormous market opportunities for commercialization.
- Enviro-economic constraints need to be addressed by process optimization.
- Reframing policies with government subsidies will increase market credibility.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Biorefinery
Circular bio-economy
Microalgae
Market
Research trend
Enviro-economic feasibility

ABSTRACT

Microalgae as an alternative feedstock for sustainable bio-products have gained significant interest over years. Even though scientific productivity related to microalgae-based research has increased in recent decades, translation to industrial scale is still lacking. Therefore, it is essential to understand the current state-of-art and, identify research gaps and hotspots driving industrial scale up. The present review through scientometric analysis attempted to delineate the research evolution contributing to this emerging field. The research trends were analysed over the last decade globally highlighting the collaborative network between the countries. The comprehensive knowledge map generated confirmed microalgal biorefinery as a scientifically active field, where the present research interest is focussed on synergistically integrating the unit processes involved to make it enviro-economically feasible. Market opportunities and regulatory policy requirements along with the consensus need to adopt circular bio-economy perspectives were highlighted to facilitate real-time implementation of microalgal biorefinery.

1. Introduction

Population explosion, rapid urbanization, excessive petroleum based products consumption have risen huge questions linked to energy security, climate change and has led to tremendous environmental damage, thereby directing a paradigm shift towards utilization of bio-based

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https://doi.org/10.1016/j.biortech.2022.127038
Received 31 January 2022; Received in revised form 15 March 2022; Accepted 17 March 2022
Available online 21 March 2022

products (De Bhowmick et al., 2019). Microalgae has gained significant attention due to its ease of growth and its inherent biochemical composition comprising of lipids, carbohydrates, proteins and bioactive compounds that can be processed not only into fuel but are also been explored for several value-added products (Banu et al., 2020). Similar to the conventional petroleum based biorefinery, microalgal biorefinery also involves a sequentially integrated process chain linked to multiple and complementary product scenarios. Unlike the crop-based biorefinery, where only a single portion is used to obtain the desired product (Pimentel et al., 2009), the underlying idea in an algal biorefinery involves the complete processing of the biochemical constituents, simultaneous prevention of environmental damage to derive maximal benefits (Koyande et al., 2019a). It is thereby essential to apply the principles of green and sustainable chemistry to identify less energy intensive extraction and valorization techniques for obtaining fuel and other high value products.

Over years, algal biorefinery research has evolved dramatically with researchers exploring the biochemical properties of microalgae for obtaining multiple products. Chandra et al. (2019) summarized the potential routes for fractionation and valorisation of algal biomass into valuable bio-based products. On a very similar concept note, (Mohan et al., 2020) proposed that algal biorefinery could be made sustainable if biomass is processed to recover multiple products at higher Technology Readiness Level (TRL) levels. Parsons et al. (2020) prophesized that more focus should be laid on techno-economic analysis (TEA), life-cycle analysis (LCA) and market analysis for bioprocessing specific components from microalgae.

Undoubtedly microalgal biorefinery and circular bio-economy concepts have gained significant popularity among the scholars as the best possible way to commercialize algal technologies. Considerable knowledge and understanding have been obtained for sustainable management of algal biorefinery from the perspectives of 1). Level of bioprocess/technology involved and 2). Value-chain products supply. However, despite these advances, the real time implementation of algal biorefinery technologies is still scattered, and are especially limited or extremely lacking in the developing countries. A thorough understanding of the way microalgae based biorefinery research has progressed over time, would aid in delineating the critical loop holes and issues to be sorted for harnessing the real time benefits of the approach. Since, the stakeholders and investors are not intimidated about the scientific research status, a systematic analysis to explicit the emerging trends and research gaps are essential. Thus, the present study used a detailed scientometric analysis, segregating the entire algal biorefinery research works from scientific database into the energy-based products [EBPs] and value-added products [VAPs] to visualize the research evolution and collaborative networking. The major purpose of the study was to summarize the established and emerging clusters of subject area to derive a comprehensive knowledge map guiding further research. Market opportunities for algal EBPs and VAPs were identified, and challenges based on enviro-economic and regulatory aspects were elucidated. Furthermore, the perspectives based on zero-discharge circular bio-economy were also highlighted. The review is likely to guide the stakeholders and researchers in scaling up algal biorefinery into a sustainable commercial market in future.

2. Algal biomass as a resource for sustainable biorefinery: Current state-of-art

Microalgae are solar cell bio-factories utilizing the central mechanism of photosynthesis, to fix carbon dioxide (CO_2) into metabolically rich biomass with 7–23% lipids, 5–23% carbohydrates and 6–52% proteins as described by researchers like Wijffels et al. (2010) and Chandra et al. (2019) to name a few, and can be explored for several commodity products. Algal lipids based on the quality can be fractionated and converted into omega-3-fatty acids as bulk chemical or could be converted into biodiesel via transesterification (Wijffels et al., 2010). Carbohydrates can be processed as an alternative to conventional starch usually obtained from the first- and second-generation crops during the fermentation processes to produce bioethanol or can be used in the food/feed industries. Algal proteins could act as a source of feed for livestock, poultry or in aquaculture. Apart from the major cellular biomolecules, long chain fatty acid molecules, pigments present in microalgae could act as a source of food additives/nutraceuticals, pharmaceuticals and health supplements. Thus, under optimized biotechnological processes, microalgae can act as a single common feedstock of renewable substrates sorting out the food and energy security issues.

Several reviews articles exist associated with the application of microalgae industries by Wijffels and Barbosa, (2010); Ruiz et al. (2016) and the algal biorefinery framework by Subhash et al. (2022) and De Bhowmick et al. (2019). Subhash et al. (2022) reviewed in detail about technological progress and constraints linked with upstream and downstream strategies for exploration of products in algal biorefinery, outlining the existing challenges. The study by De Bhowmick et al. (2019) have summarized the biofuel and VAPs to be explored from integrated wastewater effluent and flue gas treatment. Mishra et al. (2019) detailed the recycle and use of liquid effluents that could improve the feasibility aspects of utilizing microalgae in a zero-waste biorefinery concept providing a functional bioprocessing advantage for exploring multiple bio-based products. The review by Maurya et al. (2016) summarized that after bulk lipid extraction, de-oiled algal biomass with surplus biochemical constituents could be processed via bio/thermochemical routes into biofuel, feed/fertilizers or industrially relevant platform chemicals. Challenges pertaining to techno-economic and environmental feasibility of algal biorefinery have been detailed by Banu et al. (2020) and Koyande et al. (2019a) without much focus on the market entry and associated policy frameworks. Most of the existing state-of-art thus provide a comprehensive summary from the perspectives of the bioprocess involved at different steps of bio-based products exploration. Few of the earlier scientometric studies on microalgae by Konur (2011), Garrido-Cardenas et al. (2018), Li and Zhu (2021), and Konur, (2021) mostly dealt with the evolution of research linked with algal strains and wastewater treatment for bioenergy applications. Despite the literature described above, the visualization of knowledge on microalgal EBPs and VAPs correlating with their market availability are sporadic till date. The collaboration network between countries, evolution of research, emerging trends and research gaps associated with microalgal biorefinery has to be emphasized to promote the sustainable green environment.

3. Overview of the microalgal biorefinery

3.1. Global scientific research status of microalgal EBPs and VAPs

The research related to EBPs and VAPs from algae has expanded in several countries across the world (see supplementary material). China having contributing percentage of 16.4% and 12.2% is the leading country on algal EBPs and VAPs based research respectively. After China, follows United States (US) and India with contribution percentage of 11.4% and 9.39% for algal EBPs and, 10.4% and 6.2% of algal VAPs respectively. This could also be validated through these countries' largest share in algae market expanding numerous products.

In case of China and US by analysing the highly cited articles in algal EBPs, it could be interpreted that early research has focussed over the evaluation of bio-fixation potential of microalgae and fatty acid profile for sustainable biofuel production and climate mitigation. In India, the potential of microalgal biofuels has been explored and innovative search for cost-effective technologies to cultivate and harvest algae for enhanced lipid production and subsequent utilization for energy recovery and VAP production has been carried out as summarized by Pragya et al. (2013). With years passed extending the collaboration network of China with USA, Taiwan, Pakistan, United Kingdom (UK) and other countries, the research evolved to techno-economically validate the integrated process of microalgal cultivation and simultaneous resource reutilization to achieve feasible process commercialization. Meanwhile, metabolic profiling of microalgae to understand lipid enhancement mechanisms and process optimization of feasible cultivation, harvesting, transesterification to reduce the economic gap associated with it were studied (Xin et al., 2016). In US, thermochemical conversion reactions of microalgae to obtain bio-oil containing higher heating value with desirable compounds and the recovery of renewable drop-in fuel for fossil-based refineries has also been carried out with understanding the effect of process parameters (Chen et al., 2013; Reddy et al., 2016). Recent focus is on multiple product recovery process design for production of bio-hydrogen, extraction of proteins and other bioproducts to achieve significant biorefinery complexity index as detailed by Chandra et al. (2019).

In perspective of European countries, the strategies for simultaneous nutrient recovery, CO_2 sequestration for harnessing products in algal biorefinery is being researched to bring 51% reduction in energy consumption, thereby improving overall process sustainability (Ruiz et al., 2016). A collaborative study between France and Spain projected that *Chlorella sp*., grown in urban wastewater (2.70–2.91 g/L) resulted in nitrogen consumption (95% nitrogen removal) leading to progressive nutrient limitation increasing the biofuel production efficiency (Caporgno et al., 2015). The research has also been focussed more on utilizing microalgae to recover energy by directing it to anaerobic digestion for producing methane and recycling of nutrients. In Spain and France, the studies related to investigating the efficiency of different pretreatment techniques (Passos et al., 2014), biomass composition and substrate to inoculum ratio on solubilisation and anaerobic digestion of microalgae has been carried out to understand the strategies to increase methane production (Alzate et al., 2012; Caporgno et al., 2016). Tian et al. (2018) reported that acclimation using microalgae in continuous stirred tank anaerobic digester is one of the potential solutions to prevent ammonia toxicity during biogas production. In addition, the analysis of changes in microbial community structure through sequencing also aided in understanding the influence of microbiome thereof. Andreeva et al. (2021) from France in collaboration with Russia (0.50% and 1.50%) identified that chemical additives stimulate the accumulation of algal carbohydrates which could be used for the application of bio-hydrogen production.

Microalgal biorefinery research started lately in ASEAN countries and initial research focussed on process optimization of microalgae cultivation to produce higher biomass and lipid productivity for biodiesel application with simultaneous CO_2 mitigation and on exploring the strategies for lipid enhancement. For instance, Thawechai et al. (2016) in Thailand obtained 1.3 g/L and 0.5 g/L of biomass and lipid productivity respectively optimizing the light intensity and CO_2 feed rate. Sirikhachornkit et al. (2018) used nitrogen deprivation technique to enhance lipid accumulation. Molecular mechanisms indicated that nitrogen deprivation promoted the carbohydrate and lipid accumulation inhibiting the photosynthetic pigments and cell growth. Collaborative network between India, South Korea and Egypt experimented the cultivation of *C. vulgaris* in tertiary municipal wastewater supplied with 15% CO_2 for maximum nutrient removal in lesser time (Ji et al., 2013). Similarly, the researchers from Malaysia, Japan, Bangladesh and China also observed cultivation of microalgae with cost-effective medium that promotes resource reutilization for biomass growth and pigment production (Li et al., 2019). Now the research is progressing towards the integration of biomolecular and bioprocessing strategies to enhance the lipid production (Behera et al., 2021a) in collaboration with Thailand and Malaysia.

Network collaboration among countries resulted in many outcomes in algae-based VAP research. Production of VAPs like lutein, glycogen under nitrogen limited conditions were conducted in Japan (Aikawa et al., 2012). In a collaborative work between India and Japan, higher activity of superoxide dismutase and catalase was observed under nitrogen limited conditions, which is also correlated with presence of lower reactive oxygen species resulting in higher production of lipids, carbohydrate, proteins and phytohormones (Chokshi et al., 2017). Collaboration between China and US projected that possible reutilization of aqueous phase from HTL of microalgae as the growth medium requires strain improvement to prevent unwanted toxic effects on inhibiting productivity (Leng et al., 2018). India and Czech Republic countries' researchers tried to utilize microalgae for alternative food supplements through understanding its potential antioxidant, immunomodulatory and anti-inflammatory responses (Wu et al., 2016; Koyande et al., 2019b). Recent research has evolved towards identification of tolerant strain that could withstand higher ammonium nitrogen concentrations without significant changes in physiological activity (Farahin et al., 2021) that could produce microalgal biomass and VAPs with reduced production cost. The collaborative study between Spain and Norway reported that under optimized conditions of photosynthetic efficiency, the percentage of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) from marine microalgae increased, thereby reducing the cost approximately to 12 $/kg of EPA and DHA equivalents (Chauton et al., 2015). A research collaboration between France, Norway, Qatar and Netherland isolated four algal strains from Arabian Gulf and analysed biomass growth and lipid productivity profile to evaluate its commercialization potential and carbon sequestration (Schipper et al., 2019). The strains *Tetraselmis* and *Picochlorum* with presence of EPA, DHA and fatty acid methyl esters are found to be suitable candidate for further commercial exploration.

3.2. Research hotspots and knowledge mapping

Development of a research field could be interpreted by keywords (base) and its trend over time (evolution) constituting the major thematic areas (domain). The knowledge map (Fig. 1) was thus generated based on three basic components i.e., knowledge base, knowledge domain and knowledge evolution. Knowledge base, the major foundation of the knowledge map consisted of keywords having the highest co-occurrence relevant to EBPs and VAPs as the part of algal biorefinery. The keywords "microalgae", "biodiesel", "growth", "biofuel" was found to be prominent keywords owing to higher frequency values revealing main background of research arena. The base generally included terms like bioenergy (specifically biodiesel, biofuel) under EBPs with no competition with arable lands and better capacity than oleaginous crops (Wijffels and Barbosa, 2010; Gong and You, 2014; Behera et al., 2019a). Keywords like "extraction", "pigment", "fatty acid" acting as base for VAPs related research showing their potential market demand at present. Knowledge domain represented the major thematic areas as identified from cluster analysis of co-occurring keywords represented by the cluster network of keywords generated based on similarity and major research with respect to timeline (see supplementary section). The mapping was done in the framework of a raceway pond with the domain (major identified clusters) representing the paddle wheel to drive forward the algal biorefinery research. The domain could be basically categorized into three units i.e., 1). the upstream technologies including clusters #1 in EBPs category and clusters #1, #3 and #4 in VAPs category; 2). downstream processing strategies including clusters #2, #3 and #6 in EBPs and, #0 and #2 in VAPs; 3). the application aspects comprising of #0, #4, #5 in EBPs and, #5 and #6 in VAPs. These domains or clusters provide insights into the existing research interests to circumvent the technological limitations.

In case of upstream processing, knowledge base included the commonly studied strains like *C. vulgaris*, *Spirulina platensis*, *C. reinhardtii* and *D. salina* for EBPs and VAPs. For feasible microalgal biorefinery, strain improvement with cost-efficient cultivation and harvesting techniques is crucial. Among the strains, *C. reinhardtii* is one of the earliest species utilized for physiological bioprocessing and molecular biology studies linked to biofuel. Similarly, *H. pluvialis* is a popularly researched strain for astaxanthin production (Garrido-

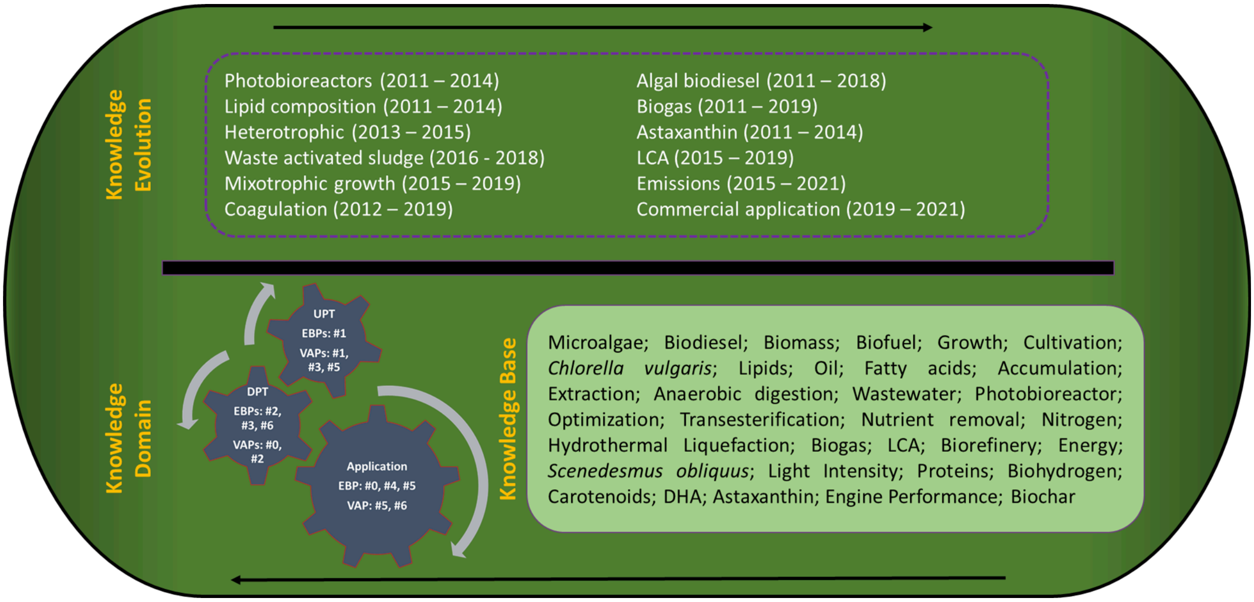

Fig. 1. Knowledge map for emerging fields of microalgal biorefinery technologies *{Abbreviations: UPT: Upstream process technologies; DPT: Downstream process technologies;* ***EBPs: Energy based products:*** *#0 – Diesel engine, #1 – Chlamydomonas reinhardtii, #2 – Hydrothermal liquefaction, #3 – Anaerobic digestion, #4 –Llifecycle assessment, #5 – Biocrude oil, #6 – Harvesting microalgae;* ***VAPs: Value-added products:*** *#0 – Lipid extraction, #1 – Haematococcus pluviallis, #2 – Hydrothermal liquefaction, #3 – Nutrient removal, #4 – Freshwater microalgae, #5 – Modern agriculture, #6 – Microbial fuel cell}*.

Cardenas et al., 2018). Only 30,000 algal species have been identified so far, thus the subject category "Biotechnology and Applied Microbiology" contributing about 15% at present to the thematic areas holds a lot of avenues for further research with the need to explore new fresh water strains having ability to sustain in alternative cheaper resources without contamination. The cluster #3 "nutrient removal" and #4 "freshwater microalgae" in VAPs depicts the research on mass cultivation with nutrient recovery from wastewater and flue gas which is also an emerging area because of unfeasible economics and sustainability issues hovering around the currently prevailing methods. Downstream processing techniques basically dewatering/harvesting and metabolic component/lipid extraction has their own pros/cons with respect to the energy requirements and environmental impacts (Subhash et al., 2022). In case of VAPs, research theme has been clustered as #0 "lipid extraction" with 135 nodes. Many lipid extraction procedures were developed and compared for its efficiency since there were no standardised procedure being adopted initially. Thus, research linked to innovative efficient cell disruption and extraction techniques involving pulsed electric field for biofuel/VAPs as described by Grimi et al. (2014), Parniakov et al. (2015) and Zhang et al. (2020) needs to be currently focussed. Compared to biochemical processing, HTL technology (cluster #2 hydrothermal liquefaction for both EBPs and VAPs) has gained interest because of its ability to process wet algal biomass deriving biocrude oil, gaseous byproducts (syngas) and hydrochar (potential application in agriculture, adsorbent and catalyst [VAPs]) with much lower energy demands and environmental impacts (Watanabe and Isdepsky, 2021). According to a harmonized model by National Renewable Energy Laboratory (NREL), freshwater algae of 105 tons/ha with 50% bio-crude conversion and inclusion of carbon credits will result in 0.24$/GGE much lower than conventional petroleum (Davis et al., 2018). Co-deoxy-liquefaction involving combined processing of microalgae and lignocellulosic biomass resulting hydrocarbon rich fuel is also an emerging research hotspot (Wu et al., 2017).

In application perspective, For EBP, cluster #0 "diesel engine" consisted of 128 nodes with silhouette value of 0.731 containing "lipid extraction", "transesterification" in initial phase explicates the research on microalgal biodiesel production which is beneficial in greenhouse gas (GHG) mitigation, however it is not economically feasible unless higher algal yield is ensured (Campbell et al., 2011). Research focussed on higher algal yield, multi-output system is being carried out, however its environmental impact and economic feasibility is still a matter of concern (Doshi et al., 2017). Cluster #5 "modern agriculture" describes algae based biostimulants and biofertilizers with potential to support plant growth without detrimental effects on environment which is another prominent interest segment with huge market opportunities (Behera et al., 2021a). It could also be validated by contribution of VAPs of 5.3% under subject category "Agriculture". The biorefinery concept of integrated wastewater treatment via algal fuel cell to produce renewable power to drive the upstream and downstream processes in algal facility along with biomass harvesting that can be harnessed into VAPs is also gaining interest as indicated by cluster #6 "microbial fuel cell".

The knowledge domain and base represented by the major clusters and co-occurring keywords respectively helps to understand the fundamentals of algal biorefinery. Technological process like growth, nutrient removal from wastewater and biochemical component (fatty acid) accumulation via nutrient starvation, further its extraction constitutes the foundation of algal biorefinery research. Finally, the growth/progress of algal biorefinery can be corroborated to the periodic evolution as demonstrated by the citation bursts of specific keywords linked to EBPs and VAPs. The period from 2011 to 2015, research was mostly focussed on the cultivation of microalgae in raceway ponds and closed photobioreactors (PBRs) to optimize the operational parameters influencing lipid synthesis and accumulation mostly for biodiesel production. Later phase of this timespan also witnessed molecular and synthetic biology approaches to enhance lipid accumulation in microalgae especially on *C. reinhardtii*, as also projected in the recent review by Behera et al. (2021b). As a part of energy based biorefinery, the period also witnessed the utilization of algal carbohydrates for bioethanol production. From 2015 onwards, the research arena has drifted towards integration of the waste resources for algal cultivation to improvise the economic feasibility. Process optimization with wastewater for efficient nutrient recovery along with carbon capture, efficient downstream steps for drying and dewatering to improve the algal yield for biofuel and VAPs like pigments as food additives/nutritional supplements were focussed from 2015 to 2021 (Ren et al., 2021). Overshadowed with the issues linked to the environmental and economic stability, LCA and TEA studies of multiple products associated with integrated zero-waste biorefinery concept facilitating commercialization and market entry are recently being investigated.

4. Market potential of microalgae derived bio-based products

4.1. Biofuel from microalgae

The global algal biofuel market is expected to grow at a compound annual growth rate (CAGR) of 8.8% reaching a value of 10.73 billion US $ by 2025 as predicted by Grand View Research Incorporation (Grand View Research, 2017). Based on the application, algal biofuel market is categorized into transportation, aerospace and defence. 70% of the total share of algal biofuel market is predicted to be accounted by the transportation sector by the year 2025, because of its enormous potential to replace diesel and gasoline in automotive vehicles. The demand for reliable and sustainable alternative to petroleum based fuel has been the major driver facilitating the industrial growth.

Geographically, the algal biofuel market is segregated into the regions of North America, Latin America, Asia-Pacific, Middle East and Africa (MEA), and Europe. With US government supporting the renewable energy sector, North America has the largest algal biofuel market having 30% of the share with huge number of start-ups. The first initiative in commercialization was also made in this direction as the US based company named Solazyme Inc. delivered 100% algal biofuel to US navy for the purpose of certification. Companies like Sapphire Energy, Solix Biofuels, Algenol Biotech, Genifuels, Blue Marble Productions, Exon Mobil are currently the major players producing algal biofuel. Solix Biofuels produces approximately 3000 gallons of algal biofuel per day (Banu et al., 2020). In US, algal open ponds with higher productivity are expected to provide an economically feasible method, approximately 70% cheaper than the conventional activated sludge based treatment, thus the co-combined nutrient remediation and exploration of algal biomass for biofuel is expected to further expedite the commercialization process. Companies like ExonMobil and Synthetic Genomics are collaboratively working in developing genetic engineering strategies to increase algal lipids production by several folds, which would lead to production of 10,000 barrels of biofuel/day by the year 2025 (Tang et al., 2020b). Countries like Germany, France and Spain are the largest producers of microalgae in Europe, with France dominating the landscape accounting 65% of the total share (Araújo et al., 2021). With a huge production capacity, European countries are expected to witness the second highest growth [12% CAGR from the period of 2018 to 2025] in the global algal biofuel market (Grand View Research, 2017). Asia-Pacific regions are also expected to witness a CAGR of over 8% by 2025 owing to the availability of cheaper raw materials, favourable climatic conditions to support algal growth. China, India and Japan are the major market players in the category of algal biofuel, with the highest share being owned by China. With better government incentives and subsidies to support the competition existing between the sustainable and renewable energy producers, a better commercialization could be achieved.

4.2. VAPS from microalgae

4.2.1. Dietary supplements, food and beverages, pharmaceutical and cosmetological products

Nutraceuticals and pharmaceuticals from microalgae categorized as genetically recognized as safe occupied the maximum share of algae based product market as of 2020 and is expected to grow further due to an increased awareness for organic, safe and healthy products by the consumers as dietary supplements, animal/aquaculture feed and personal care products.

Microalgae could synthesize polyunsaturated fatty acids like DHA, EPA, α and γ linolenic acid, along with essential amino-acids. Decrease in aquaculture yield, issues linked to ethical consumption of the marine oil, has spurred attention towards microalgal omega-3-fatty acids substitutes (Tang et al., 2020a). Microalgal oils containing DHA and EPA are being currently marketed in the form of nutraceuticals at 50 US $/kg and 650 US $/kg respectively (Koller et al., 2014). Algal oil used for nutraceuticals and biofuel has present valuation of 124.9 Million US $ (Persistence Market Research, 2021). The most commonly utilized microalgal strain for commercial nutraceutical production either as capsules, tablets/powder are *Chlorella* sp., and Spi*rulina* sp. while omega-3-fatty acids are often extracted from *Schizochytrium* sp., *Crypthecodenium cohnii, Phaeodactylum tricornutum* (Tang et al., 2020b). Pure One ™ algal oil capsules, Algae Omega 3, Nordic Naturals Algae Omega are some of the microalgae based nutraceuticals approved for marketing by the Food and Drug Association [FDA] (Tang et al., 2020b).

Major use of algal oil as food/feed supplements/additives are mostly found in the regions of Europe, North-America and East Asia. Companies in US, China, India and Germany have installed microalgal production facilities to produce 3000 tons/year Spi*rulina* sp. and 2000 tons/year *Chlorella* sp., to be sold as nutraceuticals (Katiyar and Arora, 2020). North-America basically US, Canada and Mexico hold the largest share of nutraceutical market owing to the reasons of increased population, health consciousness among the consumers. OmegaTech, an established US based company markets high quality algal oil rich in DHA with the name of “DHA gold” as health supplement. The Nuseed Nutritionals US Inc. also applied biotechnology-based bioprocess and launched microalgae-based product named “Total Omega 3 Canola Oil” in August 2021. Earthrise Nutritionals, LLC, Cyanotech Corporation, Cellana Inc. and Cargill Incorporated are some of the leading algae-based companies in North-America (Business Market Insights, 2021). Nutraceuticals from microalgae constitutes about 24% share of the European microalgae-based product application at present (Araújo et al., 2021). Based on business to business (B2B) approach, *Chlorella* sp., and Spi*rulina* sp., are marketed at 25–50 Euros/kg and 30–70 Euros/kg respectively, while the purified, finished and packaged food and feed from these algal species are sold at a higher price of 150–280 Euros/kg (Araújo et al., 2021). UK is estimated to hold 30.2% of the total algal oil market share in Europe, mainly owing to the increased population of vegans and was seen to have the largest import of microalgae fit for human consumption (Persistence Market Research, 2021). The reviews by Rumin et al. (2020) and Araújo et al. (2021) have summarized the potential of microalgae-based nutraceuticals markets in Europe. Asia-Pacific region, especially the East-Asian countries like China, India, Japan and South-Korea also hold the second highest position in the global microalgae-based health supplements and feed product market. In East-Asian market, China accounts for the largest market share (72.2%) because of higher number of algae production units and huge demand of algal products in traditional culinary, function foods and medical uses. Due to increased demand of healthy food/feed supplements, the algal oil market is also expected to witness a CAGR of 6.1% and 5.8% in Japan and South Korea respectively during the forecast period of 2021–2031. Dongtai City Spirulina Bio-Engineering Co. Ltd. (China), Fuqing King Dnarmsa Spirulina Co. Ltd. (China), Yunnan Green Biological Project Co., Ltd. (China), Taiwan Chlorella Manufacturing Company (TCMC) (Taiwan), Far East Microalgae Industries, Co., Ltd. (Taiwan), Sun Chlorella Corporation (Japan), Yaeyama Shokusan Co., Ltd. (Japan) are some of the major market players for microalgae-based food/feed products in the East-Asian region. Spi*rulina* sp., is widely cultivated in open raceway ponds due to protein rich biomass in China, Thailand and India for supplementary food/feed (Katiyar and Arora, 2020). India is also expected to see a growth in implementation of microalgae in nutraceutical industries due to increase in demand of dietary supplements by the upper- and middle-class population. Parry Nutraceuticals™ is a leading company in India selling organic *Spirulina* and *Chlorella* rich in vitamin B12 and having the recommended dietary allowance (RDA) as health supplements.

The pigments from microalgae have been long proposed to have pharmacological properties, thus are increasingly being employed in cosmetics and personal care products, food additives and health supplements (Sathasivam et al., 2019). "Chlorophyllin" a derivative of chlorophyll is popularly being used as a colorant and food additive agent (Zhao et al., 2018). As per the Global Market Insights report, β-carotene because of the potent antioxidant and immunomodulatory properties has gained immense market popularity, currently valued at 520 million US $ and is expected to grow rapidly with a CAGR of 6% over 2021–2027 (Global Market Insights Report, 2020). North-America and Asia-Pacific regions have the highest market for β-carotene. Incorporation of β-carotene because of higher bioactivity as food additives have increased its demand in China, Italy and US. Astaxanthin produced from marine microalgae, popularly from *H. pluvialis* has been increasingly gaining popularity as a healthy substitute for synthetic astaxanthin for nutraceuticals, animal and aquaculture feed (Koller et al., 2014). Currently, microalgal astaxanthin is being marketed by companies like Algae to Omega (US), Algae Health Sciences, Inc. (US), Algalif (Iceland) and Algatech Ltd. (Israel). Increased consciousness towards the incorporation of natural colourants (especially the demand for blue colour) in nutraceuticals has created a wide market for algal phycobiliproteins, especially in the Asia-Pacific regions (Meticulous Market Research Report, 2020). Microalgae with bioactive compounds having antioxidative properties to modulate melanocyte, keratinocytes, collagen stimulation are increasingly employed as cosmetological agents. Pentapharm (Switzerland) markets products like Pepha-Tight and Pepha-Ctive containing bioactive components from *Nannochloropsis* sp., and *D. salina* to stimulate skin tightening and cell proliferation respectively (Nagi et al., 2021). The rapid growth of cosmetic industry with CAGR of 5.3% during 2021–2027 is expected to reach a valuation of 463 billion US $ by 2027 providing a niche for algal cosmetics along with other VAPs (Chouhan et al., 2021).

4.2.2. Biostimulants and biofertilizers

The growing interest towards the chemical free healthy crops is expected to surge the global biostimulant market by CAGR of 13.4% starting from 2019 until the forecast period of 2025 (Meticulous Market Research, 2020). Europe has the largest share (approximately 50%) in the global biostimulant market followed by North-America and Asia-Pacific regions. Even-though most of the present share of the global biostimulants market is being occupied by the humic substances, protein hydrolysates and macroalgae based products, microalgae because of its potent high nutritive content along with the presence of phytochemicals and antioxidants has gained wide popularity in the last few years. The recent review by Behera et al. (2021a) detailed the current status of microalgae in the global biostimulant market and summarizes the challenges highlighting the need of adequate policy framework to facilitate the real-time application.

The demand of microalgae based biofertilizers has also witnessed a CAGR of 5.2% during the period of 2016–2020, surpassing the valuation of 9479 thousand US $ in 2021 (Future market Insights, 2021). The increased awareness in farmers to utilize organic and sustainable farming practices to maintain the soil fertility is expected to further spur the microalgal biofertilizer growth with 12.1% CAGR during the forecast period of 2021–2031. Fresh water microalgae, especially *Spirulina sp.*, because of its high nutritional content and capacity to achieve higher productivity and crop yield, is predicted to witness an increase in demand by the year 2031. Cyanotech Corporation (US), Cellana LLC (US), Alga Energy S.A. (Spain), Fuji Chemicals Industries Co. Ltd. (Japan) are the key players in the thematic area. Algal biostimulant and biofertilizer market is often restrained due to the issues linked with low algal productivity owing to the climatic variations and also with its high cultivation and processing costs, compared to synthetic counterparts. Companies are increasingly working to incorporate research and innovation for extending the algae based biofertilizer product portfolio to sustain with the competitors.

4.2.3. Bioplastics and biopolymer blends

The problems linked with the persistent and ubiquitous long-term presence of fossil based plastic products in the terrestrial and aquatic environment have drifted the demand towards biodegradable microbe derived bioplastics. The global bioplastic market is expected to grow at a CAGR of 5.9% during the forecast period of 2021–2026, reaching valuation of 29.7 billion US $ by 2026 (Bioplastics and Biopolymers market, 2021). The bioplastic especially from the poly-hydroxyalkanoate (PHA) is being commercially marketed by several company in US, Brazil, China and Italy. In-spite of the immense need and popularity, the bioplastic business is still at a subordinate and nascent stage and occupy only 1% of the total global plastic market (European Bioplastics, 2021). Starch based bioplastic blends occupy 21% share of the total share of biodegradable plastics. Compared to plant based starch sources, microalgal bioplastics represent a more attractive sustainable feedstock, as the latter does not compete with food sources and can be grown in waste resources (Onen Cinar et al., 2020). A company named Algix LLC (US), in 2014, established algal production facility with the government initiative to treat 10,000 acres of scum from catfish farms and produced 200 million pounds of biodegradable plastic resins. Rumin et al. (2020) predicted that microalgal bioplastics among the six sectors along with nutraceuticals, pharmaceuticals and cosmetics, biofertilizer and biofuel holds good market opportunities in Europe. Several microalgal strains like *Chlorella* sp., *Spirulina sp.*, *P. tricornutum* and *N. oleoabundans* are currently being studied to prepare biopolymer blends (Onen Cinar et al., 2020). Nevertheless, there is a need to understand the metabolism of microalgae facilitating bioplastic production to overcome the issues linked to techno-economic feasibility promoting commercialization.

5. Challenges linked to microalgal biorefinery

The strength, weakness, opportunities and threats linked to algal biorefinery commercialization are represented in Fig. 2. To overcome the issues associated with the commercialization aspects, the technical sustainability of the bioprocess involved as well as the cost and environmental feasibility of each unit process must be considered.

5.1. Techno-economic feasibility

Microalgal biorefinery can be categorized basically into two sections of 1. upstream processing involving cultivation and recovery of nutrients and, 2. downstream processing and conversion into usable products. The upstream strategies usually include costs associated with the installation of PBRs and other operational costs linked with the raw materials and resources. For commercial algae production systems to be translated into a business, it is essential to reduce the costs linked with the cultivation (Acien et al., 2012). Open ponds because of their ease of installation, operation and maintenance are mostly utilized for mass cultivation of several commercial algal strains like *Chlorella* sp., *Spirulina* sp., *Nannochloropsis* sp. and *Scenedesmus* sp. (Costa and de Morais, 2014). Open raceway ponds are successfully demonstrated for the cultivation of microalgae by Sapphire Energy Columbus Algal Biomass Farm (US) generating 520 metric tons of dried algal biomass over a period of 2 years (White and Ryan, 2015). Circular open ponds for cultivating *Chlorella sp.*, are also used in Japan and Taiwan (Dragone et al., 2010), however due to homogenous mixing constraints, these ponds could not be scaled up beyond 10,000 m^2 (Maheshwari et al., 2021). Even-though popular, the open pond configurations are often associated with issues linked to inappropriate light distribution, seasonal fluctuations and cross-contamination. Closed PBRs with much low land footprints often provide a better controlled environment in terms of light gradient, pH and mixing for optimal growth of microalgae leading to higher biomass productivity (0.2–3.8 g/L/d) than open ponds (0.12–0.48 g/L/d) (Béchet et al., 2015). However, high capital installation costs as well as huge amount of operational expenditure

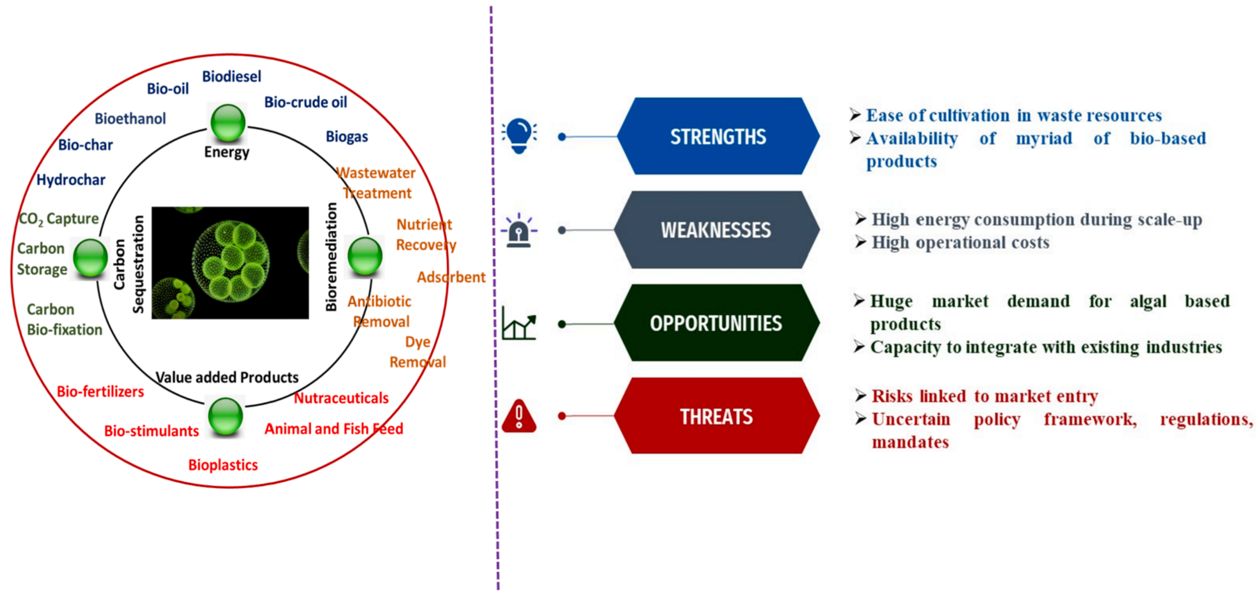

Fig. 2. Strength, Weakness, Opportunities and Threats (SWOT) analysis of microalgal biorefinery technologies.

associated with the maintenance and artificial lighting requirements in indoor PBRs often limit their mass scale industrial implementation. Also, TEA study conducted by Clippinger and Davis, (2019) at NREL reported that minimum selling price of algal biomass varies between 639 and 1737 $/ton depending on the closed PBR configuration like vertical plastic bags or vertical flexible flat panels, while it was comparatively lower (494 $/ton) in case of open ponds. Study by Banu et al. (2020) reported that bubble column PBR accounts for 81.17% of the total cost of biofuel production while open ponds account for 45.73% of share of production. The market price of the final product also plays an essential role in deciding the choice of PBRs. Thomassen et al. (2016) projected that the production of *D. salina* for β-carotene is not economically feasible in closed PBRs whereas owing to the higher market price of astaxanthin its production from *H. pluvialis* could be carried in closed PBR configuration. Nevertheless, over the last decade several strategies like the use of acrylic based stacked modular raceway ponds (Romagnoli et al., 2020) and algae turf scrubbers based open system ponds (de Souza et al., 2019) have been proposed to achieve lower land footprints, and also as strategy to overcome the issues of low algal productivity owing to the light penetration issues. Apart from reactors, the use of synthetic fertilizers as the source of nitrogen, carbon and phosphorus for sustaining microalgal cultivation also occupy an appreciable portion of the production costs (Mallick et al., 2016). Approximately, 25–5000 mg/L nitrogen and 0.98–179 mg/L phosphorous is needed during the large-scale cultivation of microalgae, which is much higher than the amount that is present in freshwater, thus is mostly met by the use of synthetic fertilizers, that adds up to the process costs (Khan et al., 2018). Use of wastewater and flue gas based carbon sequestration can drop down the algal production costs (Judd et al. 2017).

Post-cultivation process involving harvesting and conversion into bio-based products constitute a major portion of the microalgae based production costs. Diluted nature of microalgal suspension (0.02–0.05% dry solids), with size less than 30 nm and negative surface charge density often makes harvesting the most challenging task, occupying 20–30% of the total production costs (Barros et al. (2015)). Several physical and chemical harvesting methods as well as VAPs extraction techniques along with the challenges have been discussed by Subhash et al. (2022). The step by step strategy for downstream processing as proposed by Vanthoor-Koopmans et al. (2013) would aid in selection of appropriate dewatering and extraction method with reduced costs and environmental impacts.

Due to the high costs linked with the cultivation and downstream strategies during scale-up, microalgae based products when produced standalone can seldom compete with the synthetic counterparts. Valorisation of algal biomass through appropriate technology into biofuel and VAPs is expected to improvise the process economics as summarized in Table 1. Algal biorefinery depending on the type of products harnessed are classified as energy driven or material driven biorefinery. Ventura et al. (2013) analysed the performance and economic feasibility for 1000 ton/year dried algal biomass production unit considering 4 different scenarios 1). Biodiesel 2) Biodiesel combined with anaerobic digestion of residual biomass to obtain biogas 3). Biogas from wet algal biomass and, 4). Syngas production via supercritical gasification of wet algal biomass. The study projected higher net energy output (1282.42 MWh/ton) and CO_2 capture potential (1.32 ton CO_2/ton of microalgae) in scenario 4, however the revenues generated was found to be much lower than the investment in all the cases resulting in payback period of 20 years. The economics of the energy based algal biorefinery could be improvised via the combination of appropriate downstream processing strategy as demonstrated by Dong et al. (2016). The authors projected that the sequential combined processing of algal biomass subjected to dilute acid pre-treatment increased the efficiency of sugar fermentation to bioethanol and subsequent lipid extraction from the residual biomass yielding biodiesel. The study reported 37% less loss of starch during combined algal processing which also decreased the unit selling price of biofuel by 0.95$/Gallon gasoline equivalent (GGE). A recent study by Banu et al. (2020) proposed that the economic feasibility of the energy based biorefinery could be improvised by the inclusion of value-added products via the assessment of 3 different scenarios i.e., 1). Biodiesel, pigments and animal feed; 2). Biogas, pigments and two-stage fermentation; 3). Biohydrogen and pigments. The profitability and selling price of the products in algal biorefinery is also influenced by the upstream and downstream processing steps involved. Beckstrom et al. (2020) analysed the synergistic production of microalgal bioplastic feedstock and fuel co-products under the biorefinery approach projecting that the price of bioplastic feedstock varies between 970 and 6370 US $ depending on the reactor configuration (open raceway pond/cyclic flow photobioreactor) as well as the processing steps involving drying and fractionation of biochemical components. Similar to the above study, TEA by Slegers et al. (2020) reported that the revenues generated is sensitive to the cultivation conditions as well as the downstream processing involved. The study reported a profitability of 7.76 Euros/kg while *N. gaditana* is cultivated in nutrient limited conditions for lipids and peptides, compared to 7.26 Euros/kg in case of its processing to

Table 1
Techno-economic analysis of microalgae based products.

Products	Microalgae	Reactor	Extraction Methods	Software/ Method	Key Result/Inference	Reference
Bioethanol Biodiesel	*Scenedesmus acutus*	Flat Panel PBR	PAP: Solid/Liquid separation into sugars (aqueous phase); Conversion to ethanol and lipids (solid phase) extracted by hexane into biodiesel CAP: Conversion of algal slurry to ethanol via fermentation and subsequent extraction of lipids from the post-fermentation broth	Aspen	9% reduction in microalgal biofuel cost in CAP compared to PAP	Dong et al. (2016)
Protein; Peptides; Polysaccharides; Oil; Pigments	*Nannochloropsis gaditana*	PBR	High Pressure Homogenization (HPH); Centrifugation; Ultra/microfiltration; drying with HPH; Alkaline extraction (AE); Enzymatic hydrolysis (EH)	SuperPro Designer	Revenues: 11.83 Euros/kg biomass	**Slegers *et al.* (2020)**
Pigments; Protein; Oil; Peptides	*Isochrysis galbana*	PBR	High pressure pigment extraction; AE; EH	SuperPro Designer	Revenues: 8.61 Euros/kg biomass	**Slegers *et al.* (2020)**
Lipids; Peptides	*Nannochloropsis gaditana*	PBR	MF; Centrifugation; HPH; Drying; Solvent extraction by hexane/isopropanol; AE; EH	SuperPro Designer	Revenues: 16.44 Euros/kg biomass	**Slegers *et al.* (2020)**
Lipids; Pigments; Peptides	*Nannochloropsis gaditana*	PBR	MF; Centrifugation; HPH; Drying; Solvent extraction by hexane/isopropanol; Pressurized Liquid Extraction; AE; EH	SuperPro Designer	Revenues: 16.48 Euros/kg biomass	**Slegers *et al.* (2020)**
Biodiesel; Lipid extracted algae based Ni/C catalyst	*Scenedesmus* sp.,	Open raceway pond	Solvent extraction; Magnetic co-precipitation; Ultrasonication	Cost-estimation equations	Reduction in biodiesel cost from 2.03$/kg to 1.70$/kg	Mustapha et al. (2021)
Biocrude oil; Renewable naptha; Aqueous phase as fertilizer	Mixed culture	Rotating algal biofilm reactor	Hydrothermal Liquefaction; Solvent extraction	Discounted cash-flow model	Minimum fuel selling price of 11$/L via process optimization and higher yield	Barlow et al. (2016)

obtain lipids, pigments and peptides. Undoubtedly the above-mentioned techno-economic studies are suggestive of the fact that the utilization of appropriate and optimized conditions during the cultivation and, further pre-processing and conversion into usable products can increase the economic sustainability of the process.

5.2. *Environmental impacts*

LCA is often used to evaluate the energy and environmental impacts of different processing steps involved during the conversion of algal biomass into biobased products. Table 2 shows the life-cycle impacts of the algal biorefinery approach to harness multiple products. Often the cultivation stage plays a major role in governing the energy and environmental impacts. LCA studies by Monari et al. (2016) have shown that algal cultivation contributes to about 62% and 66% global warming potential (GWP) and renewable energy consumption respectively. Similar to the above study, Smetana et al. (2017) have also reported that highest impacts linked to GHG emissions, renewable energy consumption and respiratory inorganic emissions. Further, harvesting via centrifugation along with drying and extraction procedure also contributes to a major share of environmental impacts. Dasan et al. (2019) reported that dewatering and lipid extraction consumes 35–57% of the total energy, thus have a significant contribution in terms of GWP. Selection of appropriate and optimized conditions of downstream processing strategy could reduce the fossil based energy consumption. LCA studies conducted by Bennion et al. (2015) and Chowdhury and Franchetti, (2017) reported that microalgal biofuel produced via biochemical and thermochemical process have net energy ratio (NER) less than 1, making its standalone production unfeasible in terms of excess fossil energy consumption. LCA study conducted by Soh et al. (2014) proposed that GHG emissions, eutrophication and energy consumption will remain high while utilizing a single fraction from microalgae, however the use of appropriate optimized cultivation and extraction steps for obtaining multiple products under biorefinery can subsequently bring down the overall impacts. Often the results reported in the LCA studies varies creating challenges during scale-up due to the differences in assumptions, variability in process pathways and the choice of functional unit. To address this issue, a recent study by Sills et al. (2020) revealed that it is essential to analyse the coproducts allocation method in a multiproduct algal biorefinery and utilization of land based functional with system expansion can provide better comparison of LCAs.

5.3. *Commercialization status, government regulations and policies*

Over years the potential of microalgae to accumulate metabolites has aroused promising research interest in the arena to meet the existing and future industrial demands, thereby driving policies and investments. Early in (2005), several companies like Origin Oil, Aurora Biofuel, Solix Biofuel, Sapphire Energy, Solazyme, Petroalgae raised tremendous private sector investments to establish algal demonstration facilities with the aim to make biofuel competitive with the fossil counterparts. However, due to the cost in-competitiveness of algal biofuel, several companies have shifted their focus to algal biorefinery based exploration of VAPs. Although, algal biofuel has not yet reached the requisite economic targets, the LCA carried at a pilot scale algal plant at Sapphire Energy, showed lower environmental impacts and energy return on investment > 1 based on scale of production, highlighting its sustainability potential (Nagi et al., 2021). With government funding, several demonstration facilities for algal biorefinery are operational in American and European sub-continents like the pilot-scale integrated algal biorefinery Algenol (US), Algae PARC (Netherland), ALL-Gas Project (Spain), Cellana algal demonstration biorefinery (US), Global Algae Innovation for low cost production of food/fuel (US) and Muradel demonstration plant (Australia). Many research and development projects in Europe have also been scaled up and validated in relevant environmental conditions reaching the TRL of 5/6 (European Technology and Innovation Platform, 2020). The EU sanctioned the SABANA project which operates algal PBR of 1–2 ha scale in Spain and Hellin to demonstrate the economic and environmentally viable zero-waste algal biorefinery will be extended to 20 ha after validation of process technology linked with culture stabilization in municipal wastewater for use of algal products in agriculture. Multi-product integrated biorefinery of algae from CO_2 and light energy to high value specialities (MIRACLES) project coordinated by Wageningen university along with other research organizations and multinational companies operates a 10,000 tons/year facility at a TRL of 4/5. MIRACLES develops cost-effective technology through bioprospecting industry relevant strains grown in novel foam bed and membrane PBR with cost-effective harvesting and extraction of

Table 2
Life-cycle impact analysis of algal biorefinery based products.

Microalgae	Products	Process conditions	System Boundary (Functional Unit)	Software (Impact Assessment Methods)	Environmental Impacts	Key Inferences	References
Chlorella vulgaris	Biodiesel; Protein; Succinic acid	Cultivation: Seawater; flue gas (30% CO_2); Harvesting: Dissolved air floatation; Centrifugation; Flocculation with chitosan; Lipid extraction with hexane; Alkali transesterificationSolvent (Ethanol + Methanol) for protein extraction from de-oiled biomass; fermentation by E.coli for succinic acid production	Well-to-wheel [WTW] (1 kg biodiesel)	Simapro 7.3.3 (Recipe Midpoint Method)	GHG emissions Land use	Land use and GHG emission was lower considering all three products rather than only biodiesel	Gnansounou and Raman, (2016)
Freshwater algae: *Neochlorosis oleoabundans* *Chlorella sorokiniana* Marine algae: *Nannochloropsis oculata*; *Tetraselmis. suecica*	Biodiesel; Bioelectricity; Animal feed	Cultivation: Bold 3 N medium for fresh water and Enriched Sea Water medium [Nitrogen replete and deplete conditions] Harvesting: Centrifugation Lipids obtained via conventional solvent extraction combined with high pressure homogenization for protein and starch	Cradle-to-grave [CTG] (1 kg biodiesel)	Algae Process Description Module 2012 rev2 (GREET) TRACI 2 LCI	CED 1.08; GHG emissions (GWP_{100}); EP	*Neochloropsis* sp. grown in nitrogen replete condition provides EROI of 1.2 GHG emissions were positive for all cases Eutrophication impacts were higher for freshwater algae	Soh et al. (2014)
Chlorella vulgaris *Arthrospira platensis*	Food and Feed	Autotrophic/Heterotrophic cultivation in open and closed PBR; Electrical flocculation and centrifugation; Lyophilization and fractionation	CTG (1 kg algal biomass sludge/ dried biomass as protein/bulk protein from defatted algae/ oil	Simapro 8; Eco-invent 3.1 database ReCiPe and IMPACT 2002 + Midpoint impact assessment	Non-renewable energy consumptions GHG emissions; Respiratory inorganic emissions	Higher environmental impacts in all categories for open ponds Incorporation of waste resources during cultivation can bring down the impacts	**Smetana *et al.* (2017)**
Scenedesmus acutus	Bioplastic feedstock and Fuel co-products	Open pond/CF-PBR or both with fertilizer and flue gas; Flocculation and vacuum filter belt; drying; fractionation	1 kg of bioplastic	GREET Eco-invent 3.4 database	GHG emissions	67–116% reduction in GHG emissions compared to petroleum based plastics	Beckstrom et al. (2020)
Nannochloropsis sp.	Biodiesel; Biogas	Flat panel PBR (wastewater/ synthetic medium);flocculation drying; solvent and supercritical fluid extraction; anaerobic digestion of residual biomass	Well-to-tank [WTT] (1 MJ of biodiesel)	GABI and Eco-invent 2.2 database LCIA IMPACT 2002 + Midpoint impact assessment	GWP; Non-renewable energy consumptions	Higher energy and environmental impacts for algal biodiesel compared to conventional diesel	Monari et al. (2016)

Abbreviations: *GREET: Greenhouse gases, Regulated Emissions and Energy in Transportation; AP: Acidification Potential; EP: Eutrophication Potential; GWP: Global Warming Potential; CED: Cumulative Energy Demand; GHG: Greenhouse gas; EROI: Energy Return on Investment; LCIA: Life-cycle Impact Assessment; TRACI: Tools for the reduction and assessment of Chemical and other Environmental Impacts.*

valuable products from algae. With TEA and LCA, and technology validation and refinement of the business, the project is expected to reach a TRL of 7. Similarly, the D-factory project coordinated by the University of Greenwich, UK operates a 100 ha facility for cultivating *D. salina* in open and closed PBRs followed by extraction of carotenes and bioactive components using supercritical CO_2 and high-pressure counter current chromatography to be used as industrially relevant chemicals, emulsifier and polymers. Several microalgal demonstration units are also emerging in the Asia-Pacific regions. In India, the first algal biofuel facility (direct-to-ethanol) was started by Reliance Life-Sciences (Reliance Industries Pvt. Ltd.) in collaboration with Algenol Biotech (US) in Jamnagar, Gujarat in 2015 (Nagi et al. 2021). Aban Infrastructrure Pvt. Ltd. (Chennai) and Clean Environment Technology Pvt. Ltd. (Uttar Pradesh) are also working on scaling up the cultivation of microalgae concomitant with the wastewater remediation techniques for exploring the biomass as renewable fuel.

Doshi et al. (2017) suggested that the ability of algae to grow in wastewater/barren lands with the CO_2 capture capacity resulting in high value co-products in line with the government mandates for renewable energy and carbon credits will facilitate appropriate policy enforcement. However, with technology being at infancy, significant knowledge gaps exist with respect to the availability of accurate data to understand the progress of algal research thus, hindering the policy framing mechanisms. Food and agriculture organization (FAO) as a part of the United Nations provides data and statistics on algal biomass at global level. However, these data are often segmented and scattered, due to the low production capacity compared to other biomass. Though certain regions like Europe and North America, maintains databases operated by the European Joint Research Centre (EU-JRC) and NREL respectively but many developing countries lack rules and legal obligations to report the algal data in aggregated form (Araújo et al., 2021). Lack of exact reliable data makes the large-scale investment difficult in this sector, thus hindering their commercialization and market entry. Even though tools like TEA and LCA have been used to underline the feasibility of the process, they have not yet provided reliable information at sufficient TRL levels to put-forth the undermining plans and policies, especially in developing nations. Challenges linked the sufficient availability of information often questions the long-term sustainability leading to the lack of interest among the stakeholders for market launch.

Despite the high popularity and market opportunities of algae based products, the existing large-scale facilities face hindrances due to the complicated rules and regulations linked to new product entry and consumer acceptance especially in food, nutraceuticals and pharmaceutical sectors. There is a need to implement educational and awareness programs by the government to highlight the essential features of including algal supplements in diet.

6. Future directions and perspectives on circular bio-economy

The sustainability of the algal biorefinery process is often questioned with respect to the technology demands, unfeasible economics and environmental concerns. De Bhowmick et al. (2019) and Mohan et al. (2016) have rightfully pointed out that the major challenge in implementation of algal biorefinery lies with integrating the process technology in a manner to reduce the generation of waste streams improving the environmental and economic feasibility. Integration of circular bio-economy to create a zero-waste algal biorefinery (Fig. 3) via combination with waste management process is expected to improve its overall sustainability.

Microalgae has the capacity to physio-chemically remediate the nutrients and assimilate CO_2 from the flue gases in the industries (Behera et al., 2019b). Xin et al. (2016) reported the use of volatile fatty acids from food waste and centrate wastewater respectively as carbon source can bring down the cost of biofuel to 2.23–2.30 US $/gallon, comparable to the conventional petroleum-based fuel. Further, to reduce the costs linked to cultivation, the nutrient concentration must be optimized using parametric growth models as demonstrated by Figueroa-Torres et al. (2021). The authors showed that nutrient co-limitation approach with acetate as carbon source could increase the lipid and starch content by 74% and 270% respectively. Though the study was carried out on synthetic medium, it can be extrapolated to wastewater based medium to increase algal metabolite content. Gong and You, (2014) proposed an integrative zero GHG emissions based algal biorefinery recycling CO_2 from coal-fired power plant (300–2400 MW) to grow algal biomass converting them into VAPs. Authors further reported a 72% reduction in costs linked to CO_2 sequestration and utilization. Judd et al. (2017) also proposed a 35–86% reduction in costs of algal biorefinery via the use of wastewater and CO_2 mitigation.

The overall process sustainability can be increased and the input costs can be reduced by coupling algal biorefinery with the existing industries or similar complementary technologies. Ubando et al. (2016) projected that the combined heat and power as well as anaerobic digestion facilities complemented the algal biorefinery. TEA and environmental impacts assessment of integrating microalgal biorefinery with sugarcane-based bioethanol production unit as a part of earning decarbonisation credits under Brazilian National Biofuel Policy (RenovaBio) has been demonstrated by Klein et al. (2019). The study projected that co-location of algal production unit inside the sugarcane biorefinery would reduce the cultivation costs by providing CO_2 from fermentation unit and vinasse as carbon source. Furthermore, the combined unit will improve the economics of anhydrous ethanol production and will result in sequestration of 500 thousand tons CO_2 emissions/year. Technology integration under optimal conditions is expected to increase the sustainability of algal biorefinery. The review by De Bhowmick et al. (2019) suggested a renewable and sustainable strategy where the algal biofuel and biochar could be co-produced followed by valorization into VAPs.

The sustainable production and commercialization of microalgal biorefinery needs technological, environmental and socio-economic deliberations as highlighted below:

- Bioprospecting strains with potential to sustain in waste resources, recover essential nutrients metabolizing them into algal biomass
- Predictive mathematical model for resource assessment to avoid productivity loss during real-time large scale microalgal facility installation
- Combined use of genomic and metabolomics methods to understand the inherent metabolism of microalgae to accumulate biochemical components
- Innovative PBR operational technologies to reduce the water footprints, facilitate efficient gas diffusion and mass transfer improving algal productivity
- Integrating algal biorefinery with the existing infrastructure to direct the wastewater and CO_2 from flue gas stream in industries could improve the economics and reduce the environmental impacts

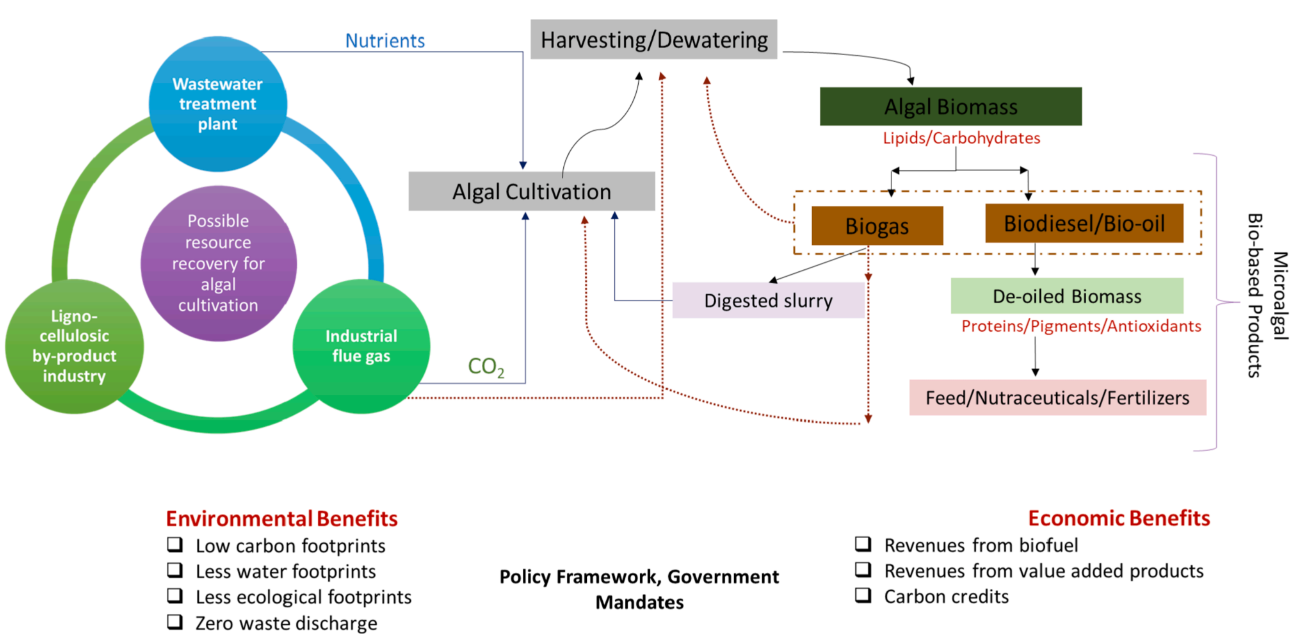

Fig. 3. Circular bio-economy perspectives for sustainable microalgal biorefinery technologies *{Red dotted arrows represents the recycle of renewable energy, blue arrows represents the supply of nutrients}*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Selection of appropriate drying and extraction technology with optimized process variables based on targeted product will help improve economic feasibility
- Step wise analysis of the upstream and downstream process techniques in algal biorefinery further their effective integration to create zero-waste discharge
- Use of relevant scale-up data and appropriate functional unit during TEA and LCA studies to provide reliable estimates
- Legal policies to maintain a consistent database for country wise microalgal research and product perspectives attracting stakeholders and investors
- Stringent rules and regulations along with incentives, subsidies promoting the market opportunities especially to small scale industries for commercialization

Apart from the above-mentioned criteria for improving the overall process efficacy and economics, it is essential to create consumer awareness regarding the advantages of the algae based products compared to the synthetic counterparts to reduce the market window for successful commercialization. Also, the logistics and the supply chain must be maintained in order to make the products readily available to consumers. Researchers, government and non-government agencies must work in cooperation to facilitate real-time implementation of microalgal biorefinery.

7. Conclusions

Microalgae acts as a sustainable feedstock with potential to generate multivariate products through biorefinery approach. Scientometric analysis of the arena revealed its evolution from the focus on exploration of EBPs and VAPs in a linear manner towards an integrative circular bioeconomy based zero waste discharge facilitating commercialization. Algal research has tremendously grown in US, European countries followed by China and India which could also be corroborated with the market opportunities. The use of resilient strains, optimization and process integration is necessary to overcome the enviro-economic constraints which along with appropriate policy framework will attract stakeholders expanding algal biorefinery global market.

CRediT authorship contribution statement

Bunushree Behera: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Mari Selvam S:** Conceptualization, Data curation, Writing – original draft. **Balasubramanian Paramasivan:** Conceptualization, Investigation, Writing – review & editing.

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.

Acknowledgements

The authors acknowledge the Department of Biotechnology and Medical Engineering of National Institute of Technology Rourkela for providing the research facility. The authors thank the Ministry of Human Resources Development (MHRD) of Government of India (GoI) for sponsoring the doctoral programme of the second author.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biortech.2022.127038.

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