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Review

Advancements in Microalgal Biorefinery Technologies and Their Economic Analysis and Positioning in Energy Resource Market

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Abstract: In the energy sector, bioenergy has been utilized as a replacement for non-renewable resources. Due to the depletion of resources, mankind may face adversities in the future. To overcome these challenges, sustainable and reliable bioenergy-based alternatives are to be used. Bioenergy sources are bio-based alternatives that have become acceptable in society for their renewability, sustainability, and environmentally friendly characteristics, but they still lag in the energy market due to their less cost-effective output of upstream and downstream processing in comparison with age-old fossil fuels. This review provides a detailed overview of their techno-economic and life cycle assessment, their positioning and competition in the energy market, and the strategies that might assist them in overcoming the market challenges. Microalgal bioenergy products have been lifting their market positioning at a slower rate that is almost unnoticeable, but their assistance in becoming a better solution against adversities of energy resource depletion in the future makes them quite promising. The new research alternatives for microalgal biomass conversion in biorefinery products for bioenergy production, which are based on combating pollution and reuse of waste products, along with the strategic application for combating the energy market competition, have also been highlighted.

Keywords: microalgae; biorefinery; biomass; bioenergy; techno-economic analysis; life-cycle assessment

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1. Introduction

Fossil fuels, as the prime energy source, are millions of years old and are depleting at an uncontrollable rate of 15 billion metric tons per year [1]. Their alternatives are bioenergy products which are the new substitutes for the depleting fuel resources [2]. Despite being a sustainable substitute, their competitive positioning in the market is not differentiating enough from fossil fuels, which are the leader of the energy resource market. Although in 2021, the global bioenergy market size was USD 108.71 B, it is expected to rise to USD 206.24 B at the end of the forecast period (2022–2030) with a 7.4% CAGR prediction rate [3]. The biorefinery market is estimated to rise by 68.5 B in the next 5-year forecast period (2022–2027) with an 8.2% CAGR [4]. It has been predicted that the algal market has a growth rate of 8.16 B in the 10-year forecast period (2021–2030) with 8.76% CAGR in the next 8 years [5]. In recent research, it has been estimated that Europe would be the second largest share in the global biorefinery market and Germany be the largest investor for the prediction period of 2022 to 2027 [4]. In the coming years, the microalgal market will have stable growth, and there will be an increase in demand for the feed and cosmetic industry on a global scale [6]. The increased popularity of biorefinery products is due to increased investments, government initiatives, consumer acceptance, rising prices due to natural resource depletion, newly introduced advancements, and minimal or net zero emissions. Valero and Renewable Energy Group in the United States and Neste in Finland

Godavari Biorefineries Ltd. in India are a few companies based on biorefinery production [4]. Although the bioenergy market has a definite position in the energy market, they are still limited by a few factors. These include high costs for their products due to high investments required for installation, different equipment used in operation, process layout designing, testing throughout multiple trials to obtain bioenergy products of high value, maintenance of the equipment, process operation and product yield, operating, and trials for the life span extension of the process finalized [7]. The capital costs of this process, along with the operation costs concerning the total product yield, when compared to the fossil fuel energy products, are considerably higher. The estimated average price of biomass-based energy generation is 6.9 cents per kilowatt hour (c/kWh) which is higher than that of fossil fuel-based energy generation (4–5 c/kWh). The cost of advanced fuel from biomass is around 65–160 EUR/MWh, while that from waste-based feedstocks is around 48–105 EUR/MWh. This cost of bioenergy is approximately 2–3 times higher than the cost of fossil fuel (30–50 EUR/MWh) [8]. Among different bioenergy sources, microalgal species are popular in biorefinery production due to their biomass composition. Several microalgal species with biomass comprising of protein, carbohydrates, and lipids in high amounts, such as *Spirulina maxima*, *Spirulina platensis*, *Aphanizomenon flos-aquae*, *Scenedesmus obliquus*, *Isochrysis galbana*, *Euglena gracilis*, *Dunaliella salina*, *Chlorella vulgaris*, and *Chlorella pyrenoidosa* with high protein content, *Chlorella zofingiensis* and *Chlorococcum* sp. with high lipid content and *Spirogyra* sp., *Porphyridium cruentum*, *Scenedesmus dimorphus*, *Scenedesmus quadricauda* and *Chlorella protothecoides* with high carbohydrate content have been used for biorefinery production [9–11]. The biomass from the algal species, depending upon their composition, is further processed into different biorefinery products: biodiesel (*Chlorella protothecoides Desmodesmus* sp., *Monoraphidium* sp., *Chlorella* sp., *Chlorella vulgaris*, *Nannochloropsis* sp., *Dunaliela salina*, *D. tertiolecta*, *Scenedesmus obliquus*), bioethanol (*D. tertiolecta*, *Synechocystis* sp. PCC 6803 and *Synechococcus elongatus* sp. PCC 7992), syngas (*Nannochloropsis oculata*), biohydrogen (*Spirogyra* sp., *Chlamydomonas* sp.), pigments (*Dunaliella*, *Scenedesmus* sp., *Haematococcus pluvialis*, *Chlorella protothecoides*, *Nannochloropsis*, *Porphyridium*, and *Spirulina platensis*), poly-unsaturated fatty acids or PUFAs (*Crypthecodinium cohnii*, *Schizochytrium* sp., *Phaeodactylum tricornutum*, and *Nannochloropsis* sp.), and many other products [12]. Differentiating the different biomass processing pathways, the main biomass to biorefinery product pathways include biochemical conversion, thermochemical conversion, transesterification, and through microbial fuel cells, which now have become a part of new algal emerging technologies [13]. These include the introduction of new strains, such as *Scenedesmus bijugus*, for better product yield, the use of hydrochar with remarkable fuel properties obtained from *Scenedesmus* sp. treated by hydrothermal carbonization at 220 °C, temperature alterations for increased biomass yield (preheating the substrate *Nannochloropsis oculata* for biomethane production, 30% yield increase observed), and many more.

The major share of 62.8% of the algal market is comprised of macroalgae [14]. In addition, the microalgal market share is expected to grow in the upcoming years, due to its application in animal feed, water purification, pharmaceutical, cosmeceutical, and nutraceutical industries and new advancements being introduced in their cultivation procedures.

The mass production of microalgae biorefinery products is usually carried out in open raceway ponds (ORPs) or photobioreactors (PBRs). The advanced new procedures such as the introduction of mixotrophic cultivation, using multiple algal strains or providing mixed culture conditions, reuse of wastewater from the cultivation process (open pond system, raceway ponds, bioreactors) or sewage sludge, flue gas from the industrial exhaust and waste-feedstocks as nutrient source introduced in microalgal cultivation methodologies, when applied for the mass production of the biorefinery products, might suffer a few drawbacks during the operation process [15]. This includes contamination due to additional microorganisms, additional heat generation, and electricity consumption for temperature maintenance, product purification, eutrophication, etc. Techno-economic analysis (TEA) and life cycle assessment (LCA) of the microalgal cultivation process assists in the evaluation of the methodology used for cultivation and obtaining biorefinery products [16]. TEA focuses on the total feasibility of the applied methodology concerning the total investment costs in the upstream procedure and the technical setup, and gains in the downstream procedure. Meanwhile, the LCA concerns the total environmental impact observed from when the methodological procedure is applied, during the process operation, and after its completion [17]. The additional bioremediation applications, when combined with the microalgal cultivation technologies, reduce the capital, operation, and overall biomass production costs. Therefore, this review concerns dealing with the drawbacks experienced during the operation of the microalgal cultivation technology for biorefinery production and the new advancements introduced to overcome limitations through the integration of environmental remediation, so that they can occupy their position in the industrial market against the regular products which rank higher in the competitive arena of the market.

2. Microalgal Biorefinery Products

The environment is getting affected due to the increase in the population, change in the climate, and depletion of fossil fuels. To overcome the dependency on fossil fuels and non-renewable resources, researchers are developing and adopting alternative and sustainable approaches. Biorefinery was adopted as an integrated process for the conversion of microalgal biomass into biofuels and other value-added products [18]. The microalgal biorefinery is a continuous process with the integration of simultaneous microalgae cultivation, product extraction, and product processing and purification. The success of the microalgal biorefinery approach is in the production of more than one product, and the important stages in microalgal biorefinery are upstream processing and downstream processing [19]. The bioprocessing of microalgae is a method of utilizing various processes to extract lipids, fats, and bioactive components from microalgal biomass, which are used as a feedstock [20]. Microalgae is utilized as a feedstock for the production of various by-products such as bioethanol, biodiesel, biohydrogen, and various non-fuel products such as carbohydrates, pigments, biomaterials, proteins, and recombinant proteins [21]. For the industrial scale, microalgae are considered a promising feedstock for the production of biofuels, carotenoids, polysaccharides, and phycobiliproteins. Therefore, significant technologies and engineering of the strains are the new trends for the upscaling of the by-products at the industrial scale [22]. Nowadays, the most promising alternative to fuels such as diesel is microalgal biodiesel which absorbs carbon dioxide for its growth and can withstand variations in high temperatures. In a recent study, *Tetradesmus obliquus* SGM19 was isolated and contained high lipids, carbohydrates, and proteins and is utilized as a substrate for the production of biodiesel, bioethanol, and glycerol, respectively [23]. The biorefinery approach is also utilized as an integrated process for the simultaneous production of value-added products and phytoremediation. In a recent study, it was found that microalgae can be utilized as a feedstock for the production of biofuels, biofertilizers, foods, and feeds, whereas it can simultaneously treat wastewater from industries that lead to water pollution [24]. The third-generation substrate, such as microalgae, is highly utilized for the production of biohydrogen [25]. The formation of biohydrogen depends on various factors such as carbon, nitrogen source, pH, temperature, and also pretreatment techniques [26]. In a recent study, *Scendesmus* spp. was used as a substrate for the formation of bioethanol [27]. The microalgal biorefinery is advantageous over other biorefineries as, in this technology, multiple products can be targeted, ranging from energy to bioactive compounds [28]. Microalgal cultivation is performed by selecting the strain, designing the layout of the process, and selection of equipment type [29]. The cultivation vessel can have different photobioreactors or open raceway ponds. The culture medium is supplied with nutrients, water, CO_2, an illumination source (sunlight or artificial light), pH regulators, temperature controllers (electricity for providing heat and water for cooling), and paddle wheels and spargers for aeration. After the biomass is collected and dewatering of microalgal biomass is performed by the microalgal biomass separation from its liquid medium. This is followed by (i) separation through sedimentation, where the biomass densifies at the bottom; (ii) through a froth flotation process, where it collects as the upper layer; (iii) biomass aggregation through the use of flocculants (alum, ferric chloride, chitosan) where the biomass aggregates, clumps and densify at the bottom, and (iv) by charge-based separation through electrophoresis [30]. The harvesting process is followed by the use of continuous flow centrifugation, filtration (belt filtration, microfiltration, ultrafiltration, rotary filtration, and vacuum drum filtration), and application of direct drying process (freeze-drying, spray drying, roller or drum drying, fluidized bed drying, infrared, and light-mediated drying). Before lipid extraction, cell lysis is performed using methods such as bead milling, homogenization, grinding, enzymatic lysis, and microwave-based lysis [31]. Other physical methods applied include mechanical disruption, use of electric fields, sonication, osmotic shock, and expeller press. For compound extraction, the common methods follow the use of organic solvents in combination, such as chloroform, methanol, hexane, isopropanol, and dichloromethane, and supercritical fluid, such as CO_2 with methanol and ethanol as cosolvents. The biochemical, chemical, and thermochemical processes involved in the production of biorefinery products vary concerning the end product [32]. The involved processes in the pathway are transesterification, supercritical fluid, ultra-sonification, hydrothermal treatment, enzymatic hydrolysis, hydrothermal liquefaction (HTL), fermentation, photocatalytic hydrogen production, combustion, and microbial fuel cell. Lipid extraction for biodiesel is performed using organic solvents, which can be either polar (methanol) or non-polar (chloroform) [33]. The separation of the lipid layer is performed using a mixture of chloroform and methanol in different ratios using Folch (2:1 v/v) and Bligh and Dyer (1:2 v/v) methods. The procedure is followed by the breaking of hydrogen bonds, cell penetration, and phase separation. Ionic liquids such as amino acid-based and cholinium-based compounds can also be utilized. In transesterification, the alcohol-catalyzed reaction results in the conversion of lipids into fatty acids, methyl esters, and triglycerides. For bioethanol production, acid, and alkali-based pretreatment methods are generally followed [34]. These include the use of sulfuric acid and hydrochloric acid in acid-based methods and the use of sodium and potassium hydroxide for alkali-based pretreatment. Other methods include the use of amylase or glucosidase in enzyme-based treatment procedures. This is followed by fermentation for the production of bioethanol. The thermochemical processes, pyrolysis, and hydrothermal liquefaction are pathways used for bio-oil production. The pyrolysis carried out in the reactor can be performed in the presence and absence of the catalyst, but the liquefaction process is preferred more for bio-oil production due to less oxygen content and high energy density [33]. In a recent study, solar energy was used for the production of microalgal biodiesel. In this study, solar energy was utilized for heating and chilling operations in the process of extraction and solvent recovery, which further minimized the carbon footprint and reduced the overall energy cost [35]. For hydrogen production, the end yield varies with the pretreatment process (electromagnetic radiation, temperature increase, microbes, and enzymes such as cellulase): untreated, physical, chemical, biological, and combined treatment [36]. Integrated treatments include merging acid or alkali treatments with enzymes, temperature alteration, or microwave-based treatment. The production of bioelectricity from microalgal biomass is mediated by the use of microbial fuel cells [37]. The selected strain of microorganisms generates electricity by using different organic carbon sources as substrates. The algae act as a bio catholyte, accept electrons, produce oxygen, combine dissolved oxygen with protons, pass through the membrane while electrons cross the anode using an external electrical resistance to compete with the circuit framework, and to generate water as a by-product. The different biorefinery products, when referred for market production, compete with the products with similar applications to balance the microalgal cultivation costs. The products in the competition are usually obtained from natural resources and are cheaper due to the low cost of production. In the upcoming sections, the comparison between the microalgal biorefinery-based products with the natural resources and their market values have been discussed.

3. Comparative Product Analysis of Microalgal Biorefinery with the Resources Leading the Energy Market

The use of microalgae for the production of biofuels and other value-added products in the market requires (i) the selection of a particular strain and species; (ii) cultivation methodology selection and its operation; (iii) production of the main product and additional market valuable by-products; and lastly, (iv) interpretation of their interconnected routes. This can lead to gaining maximum profit depending upon the production, cultivation, and harvesting methodology followed. In a recent study, it was found that microalgal biomass is rich in carbohydrates which can be utilized as a feedstock for biofuel production [38]. Nowadays, a cost-effective biorefinery is needed in the economic sphere and for sustainable production. For commercialization and industrial production, microalgae are an alternative approach to biodiesel production as it shows a high growth rate and can easily be cultivated in fresh and marine water. In a recent study, researchers analyzed the technical and economic feasibility of biodiesel production from *Phaeodactylum tricornutum* using a bubble column photobioreactor, and it was found that 1811 tones of microalgae biomass can lead to the formation of 171,705 L of biodiesel per year [39]. One of the major criteria for the production of biofuels is the selection of the microalgal strain, which has high capability in biomass productivity, lipid productivity, harvestability, and extractability of oil [40]. The major focus of biorefinery technology is to separate and recover the metabolites such as lipids, proteins, carbohydrates, and pigments from microalgae and hence reducing the overall cost [41]. Other than biofuel synthesis, microalgal biomass has the potential to be used as a substrate for the production of food, feed, fertilizers, nutrition, and cosmetics [42]. Microalgae is also a rich source of pigments and vitamins and can be consumed as a source of nutrients in the diet. In a recent study, microalgal biomass of *Nannochloropsis gaditana* L2 and *Chlamydomonas* sp. EL5 was analyzed in the preparation of gluten-free bread, and it was found that inoculation of 3% of microalgal biomass leads to a 100% increase in the iron and calcium content of the bread. Nowadays, through the biorefinery approach, value-added biochemicals can be obtained from different microalgal strains [43]. Microalgae are also used for the production of biogas, which can be considered an additional valuable by-product. In a recent study, it was found that this microalgal-based production of biogas from the anaerobic digestion obtained after the oil extraction process has production values similar in comparison to the one obtained from the raw microalgae, i.e., around 500 NL kg^{-1} VS [44]. Although microalgae have a lot of potential in the formation and commercialization of biodiesel, there are certain limitations and drawbacks. The yield of biomass is comparatively lower than the nutrients supplied [45]. Nowadays, new strategies can be adopted for the production of biofuels, biochar, and bio-based products using wastewater in the biorefinery model. A new concept of "Zero waste discharge" is a new emerging technology present in the market as it works on the strategy of the process integration for the production of 'high-value-low-volume' and 'low-value-high-volume' microalgal products with the utilization of the different wastewater combined with the use of flue gas [46]. In Figure 1, the steps for the production of various by-products from microalgae are discussed.

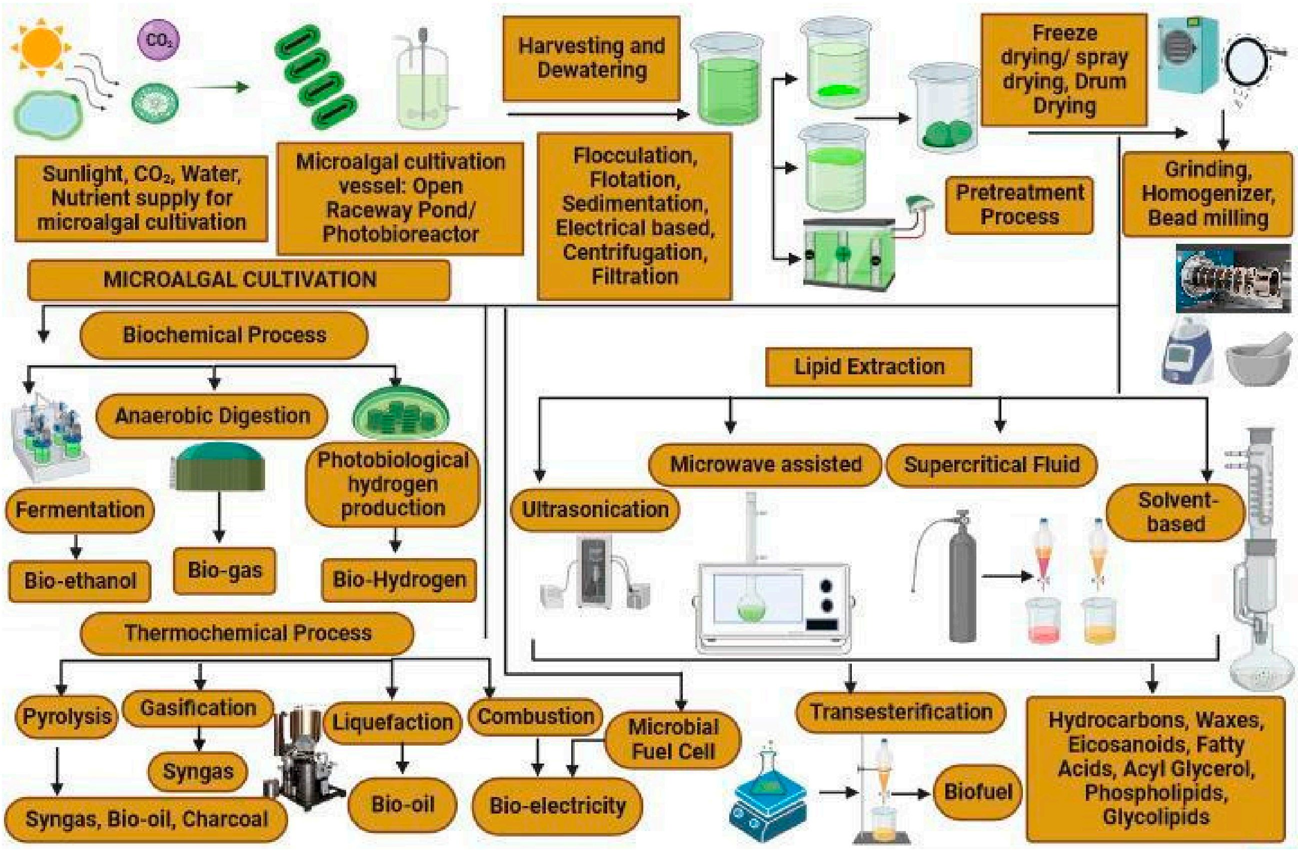

Figure 1. Schematic diagram for production of microalgal-based biorefinery products.

4. Existing and Emerging Microalgal Cultivation Technologies for Biorefinery Products

The cultivation of microalgae follows three major metabolic routes for cultivation, which are autotrophic, heterotrophic, and mixotrophic [47]. The most common type of culture system for the growth of microalgae is the autotrophic cultivation system. In the autotrophic system, sunlight is the main source of light, and the scaling up of the growth is mainly in outdoor conditions to enhance the lipid content [48,49]. The heterotrophic culture has a high growth rate, and in a recent study, it was found that two-stage cultivation can be performed for biofuel production [50]. The cultivation of microalgae can be performed majorly in open and closed systems. For the large-scale production of microalgae, open systems are preferred as they are convenient and easy to use, whereas, in closed systems, the conditions for the growth and harvesting of microalgae can be controlled and optimized as per the needs. The large-scale production of microalgae does not require fertile land, freshwater, pesticides, or herbicides, and the microalgal biomass can be produced from various wastewater resources [51,52]. A detailed description of the existing and emerging microalgal cultivation technologies are described in the next section.

4.1. Open System

Open systems are the most used systems for the growth of microalgae as they require less investment in construction and are more energy efficient for microalgal cultivation for low-cost biorefinery products. The most commonly used open system includes open ponds, which can be classified into unstirred raceway, circular, and raceway depending on the growth conditions provided for the culture, i.e., whether the mechanical mixing is applied, restricted, or absent during the cultivation process in an open pond. The microalgal species which are grown in the open pond system are *Spirulina*, *Chlorella*, and *Dunaliella* [53]. In the open raceway system, there are circuits of parallel channels in which paddlewheels are used for the cultivation of microalgae, and they are generally referred to as stirred raceways. In a recent study, it was found that open ponds are most suitable for the biorefinery models of production of fuel as they have high production of biomass and require less light consumption [54]. The first artificial open pond system was a circular pond with a depth of 30–70 cm and a width of 45 m, comprising of rotating agitator to facilitate mixing and prevent biomass sedimentation [51]. The limitation of this system is that the size is larger, the construction cost is high, and the high requirement of energy is essential for agitation [52]. In a recent study, it was found that biorefining of microalgal biomass in a circular loop enhances resource recovery and is a self-sustainable and environmentally friendly approach [55]. The global wide commercial microalgal biomass production (approximately 98%) for value-added products mostly utilizes pathways following biomass generation from open raceway ponds [56]. In a recent study, it was found that microalgae *Chlorella minutissima* was cultured in a 1500 L raceway open pond by using a commercialized biofertilizer and semi-continuous mode, and results showed 31.43 mg/L/day average lipid productivity from 162.0 mg/L/day average biomass production [57]. Another type of raceway system includes novel stacked modular open raceway ponds, which is a new emerging cultivation system for the cultivation of microalgae as it overcomes the limitations of the current cultivation technologies, as it reduces the usage of the land, and also decreases the cultivation cost [58]. This technology creates significant advantages over others by allowing an appropriate area: volume ratio for growth medium for the concentration of the microalgae. This, in turn, leads to a reduction in land use, GHG (greenhouse gases) emission, and cost of investment, ultimately leading to sustainable results while evaluating its LCA performance. This system consists of (i) an improved mixing system, (ii) a CO2 absorption system, (iii) a lighting system with both sunlight and artificial illumination, (iv) a modular design, and (iv) the use of transparent material.

4.2. Closed System

A photobioreactor is a sealed, illuminated cultured vessel used for the generation of microalgal biomass [59]. The biomass of algae is converted into various value-added by-products, which is followed by the commercialization of these products. In the closed system of photobioreactors, the growth conditions and the parameters such as temperature, light, and nutrients can be controlled, which leads to maximum production, and the chance of external contamination is also reduced [60]. In this system, the mutual shading and light distribution over a large surface are also reduced, which minimizes photo-inhibition and photo-oxidation [61]. The main advantages of photobioreactors include the increase in gas transfer, prevention of water loss, and better stripping of oxygen. In early times, flat plate-based photobioreactors were used, which were suited for both outdoor and indoor cultivation. In flat plate-based photobioreactors, the flat parallel plastic plates are closely packed, and mechanical circulation is given through horizontal channels [62]. In a recent study, a 10 m long flat plate bioreactor is used for the recovery of resources from poultry processing wastewater [63]. Nowadays, modifications in photobioreactors are used, which include tubular photobioreactors, column photobioreactors, LED-based photobioreactors, and immobilized photobioreactor systems. The tubular bioreactors are mainly used for outdoor cultivation, and the production of microalgal biomass is enhanced by aligning the tubes in different orientations, such as vertical, horizontal, helical, and inclined [64]. The major limitation of this system is that long tubes lead to poor mass transfer [52]. A new design of a closed bioreactor is a cone-bottom polyethylene tank in which fluorescent lamps are installed internally with monitoring and control systems that can measure the pH, temperature, and optical density of the microalgal culture [65]. In a recent study by Montero et al., 2020, a tubular horizontal semi-closed photobioreactor was installed in Barcelona, Spain, and this biorefinery plant generates different biorefinery products [66]. For the large-scale commercialization of microalgae to be used in the market, new technologies for the cultivation of microalgae have to be adapted.

4.3. Hybrid Culture System

Nowadays, the new concept of a hybrid culture system has been developed and used for the cultivation of microalgae. The various microalgal systems include open systems, closed systems, hybrid systems, and turf systems [67]. The hybrid system overcomes the disadvantages and limitations of open and closed systems. Although open systems are easy to maintain and possess greater surface area, they are easily contaminated and also lose high water content due to evaporation, whereas in closed systems, the conditions and parameters can be optimized, but the cost for their construction and maintenance is high. Therefore, for the cultivation and production of high-density microalgal cultures, the development of a hybrid semi-closed, thin-layer cascade photobioreactor came into the role [68]. The hybrid photobioreactor consists of two or more reaction units that are integrated such that thin layers are coupled to a system, such as bubble columns based on the height/diameter ratio and surface/volume ratio, to obtain the maximum biomass and productivity [69]. In a recent study, it was found that cultivation in the hybrid system leads to maximum biomass productivity of 0.74 g $L^{-1\,d-1}$, and a carbon bioconversion efficiency of 46.9% was achieved [70]. The carbon bioconversion efficiency refers to the proportion of carbon provided in the substrate or through photosynthesis for incorporation into the microalgal biomass for the carbon produced. The hybrid bioreactor consists of a bubbled bioreactor integrated into an illumination system. A cylindrical polyvinyl chloride is present in the bubble column reactor system, and the illumination system is arranged on the surface to provide the optimum light intensity [69]. Researchers have developed a new hybrid system, which consists of a biomass culture medium, ground source heat pump, concentrated solar corrector, active solar distiller, and biodiesel reactor. This system was used to maintain water salinity conditions of the medium for the production of *Nannochloropsis oculata* with a biomass yield of ($3.17 \times 10^6 \pm 0.50 \times 10^5$ cell/mL), which was at the maximum on the eighth day of the cultivation [71]. Scientists have proposed a new innovative hybrid system for wastewater treatment. This system consists of a biofilm reactor that works on the production of algal biomass, and the harvesting unit is connected to a high-rate algal pond; the results were quite promising [72]. In a recent study, a microalgal electroactive biofilm-constructed wetland integrated with anaerobic digestion was constructed for the swine water treatment, and the results showed that microalgal bioactive biofilm increases the stability and efficiency of the constructed wetland [73]. A hybrid algal biofilm-enhanced raceway pond was designed, which consists of a carrier material where algal cells can grow on the surface as an algal biofilm. This system has various advantages, such as the increase in the total algal cultivation area; microalgal cells grow as a biofilm, no separation or pretreatment is required for the discharge of the effluents, and the harvesting is also easy [74].

A new technology for microalgal cultivation that came into play is the algal turf scrubbers, which are utilized for controlling nutrient pollution by optimizing the natural capabilities of algae to recover excess nutrients from the water. It works on the mechanism that the growth of algal mats removes the nutrient pollutants such as nitrogen and phosphorous from the wastewater. Algal turf scrubbers were designed to treat natural wastewater. The water quality is improved by algal turf scrubbing by passing a shallow stream of wastewater over the surface of a gently sloped flow [75]. Recently, researchers have improved the performance of the algal turf systems for the removal of nutrients, and, to improve the biomass yield, a set of tiles with repeated hemispheres of different diameters was utilized [76]. Algal turf systems are used for bioremediation and also reduce the cost of the bioactive compounds. In a recent study, a strain of *Chlorella* sp. was cultivated in synthetic municipal secondary effluent, which is utilized as a culturing medium, and algal turf scrubbers resolved the water retention issue [77]. In a recent study, researchers have found that filamentous algae nutrient scrubbers have the tendency to remove the nitrogen content, and it requires less than half the land area for their construction [78]. For the large-scale commercialization of microalgae to be used in the market, new technologies for the cultivation of microalgae have to be developed.

5. Techno-Economic Assessment and Life Cycle Assessment of Biorefinery Products

The value of microalgal biorefinery products has been deemed as equal to a replacement source and a troubleshooter for the current depleting resources. The high-end cost of production makes the combined analysis of TEA and LCA essential. The capital, operating, and production costs and the economic feasibility of the process for upstream and downstream processes estimation, along with the environmental impact, gives a clear evaluation of the product's performance and its comparative status compared to the technologies in competition. Several TEA and LCA studies have been performed to analyze process production cost and feasibility of different biorefinery products, which have been evaluated based on the production pathways, techniques, nutrient composition, and product outcome. The techno-economic analysis is performed to analyze the cost, comparing the different strategies for the production and harvesting technologies. A study was conducted for the techno-economic analysis of *Nannochloropsis oceanica* for around a year. The results showed that the harvesting and freeze-drying costs for microalgal biomass were 10.65% and 20.15% of the total biomass cost, respectively, and these costs can be reduced further by 7.03% when a combination of ultrafiltration and spray drying were utilized. Hence, it can be applied to the production of foods, feed additives, aquaculture products, and other high-value products [79]. Microalgal productivity range in the case of open raceway ponds (ORP), algal turf scrubbers, and different photobioreactors (PBRs) varies from 2000 to 13,000 t km^{-2} yr^{-2}; the total cost (capital and operating) varies from USD 500 to 3500 t^{-1} [80,81]. A study based on the use of a microalgal cultivation model on a hypothetical 628 m^3 tubular PBR located in Halle/Saale (Central Germany), where *Nannochloropsis* sp. was grown for food and gave a yield of EUR 4.5 M as the net present value after 30 years (1.87% annualized return on investment); it showed an observable 47% rise in net present value with 15% increment in selling costs and decrement in cost of cultivation by 50% due to 3 fatty acid eicosapentaenoic acid production when compared with the cultivation costs of Atlantic salmon [82]. The PBR infrastructure, maintenance, and labor cost included 20–30% from the glass tube system, 21–24% from the drying system, and 18–21% from building construction, with 7% from other additional investment costs. In terms of the operating costs, the major portion accounted for 39–42% were labor costs. The total costs of this model system were EUR 8.63–11.00 kg^{-1} dry biomass. The LCA of a pilot scale study based on the cultivation and biomass processing of *Chlorella vulgaris* and *Arthrospira platensis* in autotrophic and heterotrophic conditions was conducted in Berlin (Germany) for food and feed products [83]. It stated that the non-renewable energy consumption, global warming, and respiratory inorganic emissions were the factors causing the highest impact due to (i) glucose use; (ii) electricity and energy consumption for cultivation and temperature maintenance; and (iii) lack of justification of the environmental sustainability of microalgae protein powders [83]. When *C. vulgaris* was grown under heterotrophic conditions with glucose as a carbon source, the environmental impact was 26%, while 51% of the total impact was due to electricity consumption. On the other hand, *A. platensis* grown in ORPs showed 80% of environmental impact, as changing environmental conditions required constant heating and resulted in huge energy consumption.

The LCA of most of the studies predicts the impact to be uncertain, i.e., both positive and negative. The negative result is mainly due to the heat and electricity consumption-based emissions of SO_X, NO_X, CO_2, and $PM_{2.5}$ (mainly in the thermochemical conversion process), eutrophication due to nutrient release in water bodies, steel, and PVC used in PBRs, extensive land use in ORP, and 70–90% (non-renewable) energy consumption [84]. A total of 3–15% of the biorefinery production cost (EUR 0.5–2 kg^{-1} algae) is contributed by the harvesting and the dewatering process, with the maximum energy consumption estimation of 0.2–5 kWh kg^{-1} in ORPs. The maximum cost and energy reduction that can be obtained is EUR 0.1–0.6 PBRs kg^{-1} and 0.1–0.7 kWh·kg^{-1} for the PBRs, respectively [85]. The LCA impact factors from the production processes of electricity, biofuel, proteins, feed, and pigments, from dry biomass, biochar, or biofuel, include global warming potential, abiotic depletion, acidification potential, land exploitation, smog, ionizing radiation, breathing difficulties, excessive water use, eutrophication potential, ecotoxicity potential (water bodies—marine and freshwater), photochemical oxidation, non-renewable energy consumption, and emission of several air pollutants. The TEA and the LCA of some analytical studies on the microalgal cultivation process for biorefinery production are listed in Table 1. In Figure 2, the authors list the various factors that affect the techno-economic analysis and life cycle assessment.

Table 1. Techno-economic analysis and life cycle assessment of some microalgal cultivation processes performed for biorefinery production.

	Title	Cultivation Type	Biomass/Biorefinery Product	TEA	LCA	Reference
1	Techno-economics and sensitivity analysis of microalgae as a commercial feedstock for bioethanol production	Closed system PBR	Biomass: 56 t ha^{-1} Bioethanol yield: 31,119.49 gal yr^{-1}	Total production cost: SGD 2.22 M Total bioethanol selling price: USD 2.87 M By-product sale price: USD 1.6 M	-	[86]
		ORP	Biomass: 28 t ha^{-1} Bioethanol: 25,968.13 gal yr^{-1}			
2	Integrated techno-economic and life cycle assessment of the conversion of high productivity, low lipid algae to renewable fuels	Biochemical (ATS)	Biomass (ref): 1215 t AFDW biomass day^{-1} Purchase cost: USD 515 t^{-1} AFDW	Fuel selling price: USD 12.85 GGE^{-1}	GWP: 111.2 g CO_{2eq} MJ $fuel^{-11}$	[87]
		Thermal (ATS)	Biomass (ref): 1215 t AFDW biomass day^{-1} Purchase cost: USD 515 t^{-1} AFDW	Fuel selling price: USD 10.41 GGE^{-1}	GWP: −2 g CO_{2eq} MJ $fuel^{-11}$	
3	Techno-economic and life cycle analysis of biofuel production via hydrothermal liquefaction of microalgae in a methanol–water system and catalytic hydrotreatment using hydro char as a catalyst support	Combustion	Biomass: 200 dry metric tonnes day^{-1} O_2 content: 14.5 wt% HHV of 33.4 MJ $kg_{biocrude\ oil}^{-1}$	Fuel selling price: USD 2.2 L^{-1}	GWP: −1.13 $gCO_{2\text{-}eq}$ MJ^{-1}	[88]
		Activation	Biomass: 200 dry metric tonnes day^{-1} O_2 content: (3.1 wt%) HHV: 42 MJ $kg_{biofuel}^{-1}$			
4	Microalgae to biofuels through hydrothermal liquefaction: open-source techno-economic analysis and life cycle assessment	ORP		MFSP of USD 1.17 LGE^{-1} biomass purchase price: USD 4.44 GGE^{-1} HTL: USD 0.45 LGE^{-1} (USD 1.69 GGE^{-1})	GWP: +23 g CO_2 eq MJ^{-1} Net energy ratio: 0.30 Acidification: 1.8 × 10–4 kg SO_2 eq MJ^{-1} Ecotoxicity: 1.4 × 10^{-1} CTUe MJ^{-1} Eutrophication: 3.5 × 10^{-3} kg N eq MJ^{-1} Human health: Carcinogenic: 1.54 × 10^{-9} Non-carcinogenic 6.72 × 10^{-9} CTUh MJ^{-1} Ozone depletion: 5.4 × 10^{-9} kg CFC-11 eq MJ^{-1} Photochemical ozone formation: 2.7 × 10^{-3} kg O_3 eq MJ^{-1} Fossil fuel depletion: 0.26 $MJ_{surplus}$ MJ_{fuel} Respiratory effects: 4.3 × 10^{-5} kg $PM_{2.5}$ eq MJ^{-1}	[89]
5	Techno-economic assessment and life cycle assessment of CO_2 to biofuel via micro-algae process	ORP	Biomass productivity: 30 g-algae/m^2-day	CAPEX is EUR 928 M OPEX is EUR 102 M/y Biofuel production cost: EUR 1186/t	GHG emissions: 26.6 g-CO_2/MJ	[90]
6	Techno-economic study of CO_2 capture of a thermoelectric plant using microalgae (Chlorella vulgaris) for production of feedstock for bioenergy	ORP	Biomass productivity: 12.7 g/m^2/day	Operating costs range from USD 4.75 to 6.55/kg CO_2 Capture: 102.13 tons/year Production Cost among the most efficient scenario w.r.t. energy consumption USD 4.75/kg–USD 6.55/kg	-	[91]

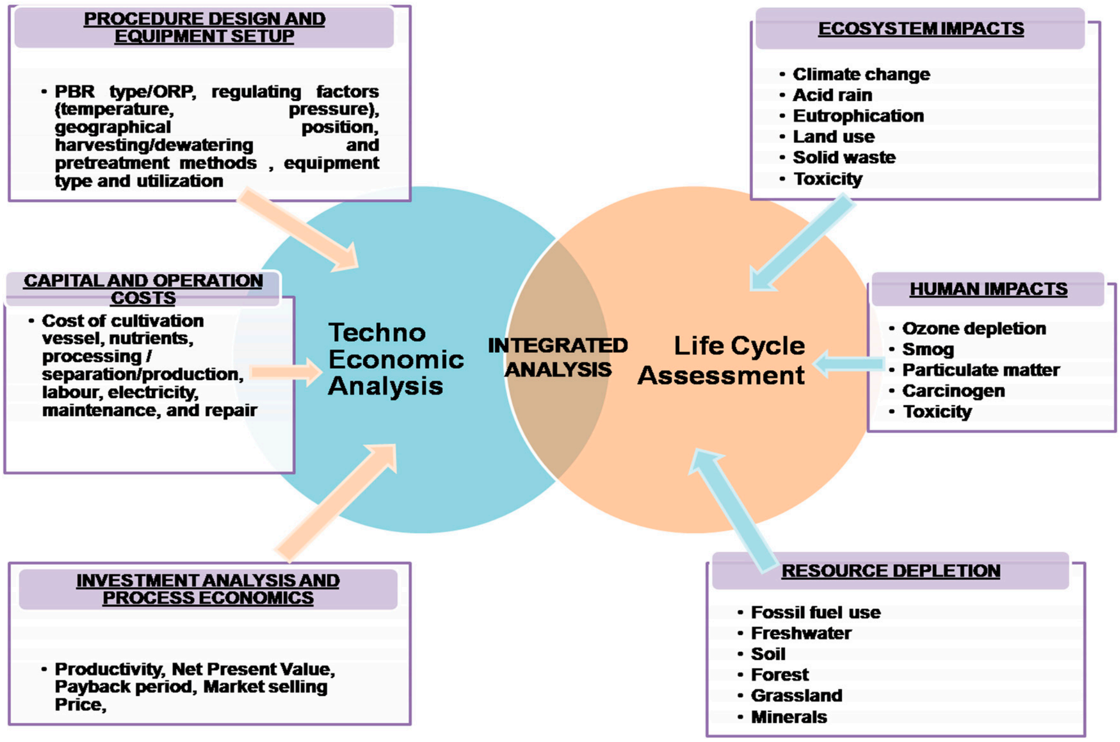

Figure 2. Factors involved in integrated techno-economic analysis and life cycle assessment.

6. Market Strategies for Emerging Microalgal Biorefinery Technologies and Future Challenges

According to the Food and Agriculture Organization of the United Nations, Asia occupied 59.10% of the global algal market in 2021 (with 11.4% CAGR in the forecast period) by contributing at least 99.10% of the total cultivated algal production in 2019. This is followed by North America at 19.2% global algal market share in 2021, with 8.6% CAGR in the next 10 years (2022 to 2031) [92]. Even though the onset of the pandemic caused China, the leader of the microalgal production market, to fall, the current market statistics state that by the end of the forecast period 2021–2031, the microalgae market may turn from the value of USD 20.16 billion (2021) to USD 55.67 billion (2031) with 10.9% CAGR [14]. Since the global nutraceuticals market is expected to grow by USD 164 billion by the end of the forecast period of 2017- 2025, while the Indian nutraceuticals market will grow by USD 14 billion, the microalgal products with nutraceutical value have a high opportunity of occupying the major share of the market due to their high in demand properties of anti-aging, immune booster, and health supplement [93]. The products such as omega-3 fatty acids (linolenic acid, alpha-linolenic acid, eicosapentaenoic (EPA), and docosahexaenoic acid (DHA)), pigments (astaxanthin, phycoerythrin), vitamins, amino acids, and other products are regarded as valuable in the microalgal market because of their health-related applications. Several international companies from the United States, Israel, Australia, Hawaii, and India have opted for the production of biorefinery products. These include Sapphire Energy Inc, Cellana Inc, TerraVia Inc, BioReal Inc., Algenol Biotech LLC, Synthetic Genomics Inc, Algatech, Solix Biofuels, Seambiotic, Algae. Tec., CyanoTech Corp., Proteus Corp., Parry Nutraceutical Division, BlueBioTech Int. GmbH, Euglena Co. Ltd., Sea6 Energy, and Muradel Pty Ltd. [94]. Their production ranges from 100 million to 1 billion gallons per annum with a revenue of USD 93,000–16.8 M [95]. Since the production cost of microalgal cultivation for biorefinery products is high, the production value and economic feasibility of the process are stressed for improvement so that the overall gain value can be improved. The extraction process and the utilization pathway of the wet microalgae have been subjected to multiple modifications for better output results, such as the use of aqueous extraction techniques and mild liquid-based extraction [96].

Several patents have been filed in the past 5 years, tailored oils by Terravia Holdings Inc (US9719114B2), algal oil and biofuel and methods of producing the same by Yeda Research and Development Co. Ltd. (WO2017033188A1), microalgal flour by Solazyme Roquette Nutritionals, LLC (US10098371B2), Protein-rich microalgal biomass compositions of optimized sensory quality by Corbion Biotech, Inc. (US10119947B2). Some of the algal companies with their biorefinery products have been listed in Table 2. These companies, along with microalgal cultivation, maintain the equilibrium between the upstream and downstream processing by production and selling of biorefinery products along with the co-products with high value.

Table 2. Algal Companies in Global Market with their biorefinery products.

	Company Name	Location	Compounds	Products	Reference
1.	Algatechnologies, Ltd.	Israel	Astaxanthin, fucoxanthin	AstaPure® Arava, FucoVital Fuxocanthin, Astapure, AstaPure®Max, BioGlena™, FucoVital™, Bioecolians	[97]
2.	BASF SE		Beta carotene, lutein, linoleic acid, omega-3 fatty acids, saccharides, vitamins	Dehyton® AO 45, algal betaine, Betatene®· Dry n-3®, Lucarotin®, LycoVit®	[98]
3.	ADM	United States	DHA	Onavita DHA Algal Oil, Onavita Flaxseed Oil	[99]
4.	Corbion NV	Amsterdam, the Netherlands	Omega-3 fatty acids	AlgaPrime™ DHA.	[100]
5.	Cyanotech Corporation	USA	Spirulina biomass, microalgal extracts	BioAstin® Hawaiian Astaxanthin® Hawaiian Spirulina	[101]
6.	E.I.D. Parry India Ltd.	India	Chlorophyll, essential vitamins, minerals, and fatty acids, astaxanthin, zeaxanthin, lutein	SpiruZan® (Spirulina with Astaxanthin) Parry Organic Spirulina, FlexPro MD®, USPlus® Saw Palmetto	[102]
7.	Fenchem Biotek Ltd.	China	Betacarotene, astaxanthin, zeaxanthin, lutein	AstaSuper™ Astaxanthin, BetaOne™, Hawaiian Astaxanthin Softgels, Water DispersiblePowder	[103]
8.	Royal DSM N.V.	The Netherlands	EPA, DHA vitamins, carotenoids, cannabinoids, zeaxanthin	OPTISHARP® redivivo® Lycopene FloraGLO® Lutein CaroCare® (natural Beta-Carotene) AstaSana™	[104]

The main challenge for microalgal cultivation is the capital investment, the mass land area requirement (especially for ORPs), and the additional essential cost expenditure on operation, maintenance, and continuation of the technological process of the setup. Although biorefinery products are considered a sustainable approach, the main challenge lies in the methodologies followed for the production of these high-value compounds. Additionally, the LCA of the total environmental impact that the process has is considered to be in the in-between zone where it can neither be called a positive approach towards sustainable technology nor a negative one. The strict guidelines set by the government also do not allow microalgal biorefinery products to enter the competitive market. Certain requirements are required to be met where the algal products can be used as a replacement, such as in the case of algal fuels while competing with petroleum, high oil production, low maintenance species, improved cultivation, biomass conversion process, and cost effectiveness. Current algal fuel production cost is 4–70 times more than petroleum costs.

This is due to the imbalance and large gap between the upstream and downstream processes of microalgal cultivation for biofuel production. The real market competition of microalgal biorefinery products with the other cheaper technologies and resources is quite difficult since the competition lies between bio-based fuel with high investment cost and the fuel (natural resource), which took millions of years to form. Similarly, for the other biorefinery products, the high cost of biomass conversion renders the cost unbalanced in terms of the total profit gain values. To combat these setbacks, microalgal companies have been known to work on extra output efficiency to increase their profits.

7. Integration of Market Strategies for Microalgal Biorefinery Technologies with Environmental Bioremediation

The knowledge of the expensive microalgal cultivation costs and the necessity for the new remedial technologies against pollution, when combined, brings a solution for multiple problems faced by mankind due to anthropogenic activities. The integration of renewable energy and wastewater technology gave better analytical results in TEA and LCA studies of microalgal cultivation for biorefinery products. The alterations made in the microalgal cultivation process have not only brought down the capital and operating costs, but also the biomass production costs. The optimization made for the photosynthetic efficiency (increased twice), temperature (20 °C increase), alternative urea source (75% decrease), and wastewater treatment cost (50% decrease) made in the four-cultivation system: horizontal tubular photobioreactors (HTPBRs), vertical stacked horizontal tubular photobioreactors (VSPBRs), flat panel photobioreactors (FPBRs), open raceway ponds (ORPs), led to highest biomass recovery of 62–74 t ha^{-1} yr^{-1} in VSPBRs and lowest of 34–41 t ha^{-1} yr^{-1} in HTPBRs and production cost of EUR 2.9 kg^{-1} with 25–45% cost reduction [105]. An LCA study for wastewater-based algal biofuel production was carried out using the spatially -explicit -high -resolution life cycle assessment (SEHR- LCA) model for the combinational integration of four modules: high-resolution GIS-based (geographic information system) spatial resource assessment, spatially explicit algae growth model, biofuel conversion pathways and LCA [106]. Among the three different processes applied for bio-fuel production: HTL had the highest energy output of 1.75×10^{11} MJ/yr and the highest bio-oil productivity of 0.98 billion gallons/yr, which was followed by microwave pyrolysis (MP) and lipid extraction (LE). Both HTL and MP had the highest biochar productivity of 1.8 million tons/yr, while MP had 2.44 million tons/yr biogas production. The improvements required in technical designing for efficient consumption of energy and land use, along with the use of wastewater as an alternative nutrient resource, might result in better ideal biomass production, lipid extraction, and microwave pyrolysis. A comparative LCA study was performed for the cultivation of *Phaeodactylum tricornutum* in column PBR for high-value compounds such as omega-1 fatty acids (EPA) using synthetic CO_2 supply or by the use of waste CO_2 from a biogas upgrading process hypothesizing industrial symbiosis network (hypothesis made on the basis of experimental data) [107]. The use of waste CO_2 gave better LCA results because of the lack of production process, which is present in synthetic CO_2, and high production value. Along with this, several impact factors' value was found to be lower, with significant differences in the value of acidification potential, global warming potential, human toxicity potential with cancer effects, and photochemical ozone formation potential when waste CO_2 was used. Since the TEA and LCA analytical results were better when the bioremediation initiatives were merged with the microalgal cultivation process, it is required that more studies need to be analyzed for reconfirmation of their applicability. The integrated studies where the bioremediation process is combined with the microalgal cultivation process for biorefinery production are mentioned in Table 3. Therefore, the introduction of cost-effective technologies and their integration into microalgal cultivation might yield better results.

Table 3. The techno-economic analysis and life cycle assessment of bioremediation integrated microalgal cultivation processes biorefinery production.

	Title	Cultivation Type/Process	Environmental Remediation	Biomass/Biorefinery Product	TEA	LCA	Reference
1.	Evaluating the potential of renewable diesel production from algae cultured on wastewater: techno-economic analysis and life cycle assessment	ORP	Use of flue gas and wastewater	Biomass: 3550 kg/h Biocrude oil: 1222 kg/hr	The total cost of production: USD 38,645/ha Renewable diesel: USD 1.75/L (USD 6.62/gal). Bio-oil production plant: 105 MM w.r.t. Renewable diesel: 10 M L yr^{-1} (2.7 M gallon Lyr^{-1}) Renewable diesel price: USD 6.62/gal	Fossil fuel energy used: 241.6 MJ per 1000 MJ Net energy value: 758.4 MJ per 1000 MJ GHG emissions: –3.73 kg CO_2 eq./L Renewable diesel	[108]
2.	Renewable hydrogen and methane production from microalgae: A techno-economic and life cycle assessment study	ORP	Waste gases from pressure swing adsorption and unpolluted wastewater	Biomass: 12,790 kg h^{-1} Hydrogen: 1239 kg h^{-1}	Microalgae cost: USD 0.5/kg (INR32.5/kg) total capital investment (TCI) of USD 144.6 M/INR9.40 B	Life cycle climatic change impact: 7.56 kg CO_2-eq/kg H_2.	[109]
				Methane: 3484.96 kg/h	TCI: USD 78.61 M Million/ INR5.11 B	Life cycle climatic change impact: 1.18 kg CO_2 eq/ kg of CH_4	
3.	Sustainability of carbon delivery to an algal biorefinery: A techno-economic and life-cycle assessment	ORP	CO_2 sources: atmosphere; power plant waste emissions; concentrated from waste sources and compressed inorganic carbon in the form of hydrogen carbonate; organic carbon in cellulosic sugars (corn stover)	Biomass (constant/ baseline): 506 metric tons day^{-1}	MFSP, USD 6.47 GGE^{-1}, Effective cost range: 135–400 USD metric ton^{-1} carbon	GWP: 28.1g $CO_{2\text{-eq}}$ MJ^{-1} NER: 0.13 MJ MJ^{-1}	[110]
					Pure sources of gaseous CO_2: uncompressed (pipeline transportation ≤40 km) and compressed and supercritical (pipeline transportation ≤100 km): Effective cost: <0.50 USD GGE^{-1} GWP: <20 g $CO_{2\text{-eq}}$ MJ_{-1}		
4.	Techno-economic analysis of microalgae-based liquid fuels production from wastewater via hydrothermal liquefaction and hydroprocessing	ORP	Wastewater	Algal productivity: 586 tonnes /day hydrocarbon fuels productivity (tonnes per annum) Diesel: 6471 Jet: 21,083 Gasoline: 54,981 H2: 391	Minimum selling price (MSP) (hydrocarbon fuels): USD 4.3/GGE	-	[111]
5.	Comprehensive techno-economic analysis of wastewater-based algal biofuel production: a case study	PBR	Wastewater	-	Total project Investment: 5,352,657 Total Annual cost: 1,977,831 selling price of biofuel: USD 2.23/gallon Cost savings and revenue: wastewater treatment cost saving 564,768 Syngas income 47,607	-	[112]

8. Future Directions and Recommendation

Microalgal biorefineries are limited by different factors, which include several drawbacks suffered during the production process. The overall zero-waste production, or an ideal process for bioenergy generation, is unachievable and requires several new research methods to be incorporated into the industrial processes to achieve them. The use of flue gas or wastewater creates irregularities in algal biomass composition, making their processing difficult and more costly for biorefinery production. Additionally, the environmental factors that regulate the cultivation process play a major role in biorefinery production, as their composition varies for the value of regulating factors [113]. These include pH maintenance, temperature variance, illumination source and intensity, mixing or circulation speed, nutrient availability, CO_2 and water source, cultivation vessel type, and weather. During the overall production process, different strategies employed for the production of a single type of biorefinery product turn the process costly. The downstream process has been estimated to contribute to about 40% of the total production cost [114]. This makes the overall process to be less cost-effective.

The incomplete information on the comparative analysis between different microalgal cultivation procedures makes it difficult to strategies new methodologies for better output results. So, the foremost step towards the new pathway is the analysis made based on the previous microalgal cultivation-based studies. As Tim Granata analyzed a total of 317 reactor-based studies on microalgal cultivation, it was observed that about 45% of studies were performed using green microalgae (19% *Chlorella* sp.), followed by Cyanobacteria 27% and *Spirulina* 24% [115]. The research findings concluded the following: maximal growth rates of microalgae were inversely proportional to cell volume. As for the larger (≥100 μm^3) cell volumes, the growth rate of different microalgae exceeded in the bioreactor than their reported growth rates (in 71% of studies), while on the other hand, the biomass in the bioreactor was higher than that at the laboratory level in 86% sample studies. The production rates were overlaid by the biomass rate, the growth rate declined greatly with higher production rates in some studies, and the volume of the bioreactor and area of illumination affected the production rate and oil yield directly. The analysis of these studies helps in the application of the findings in further research to overcome the shortcomings of the cultivation process. Additionally, analysis of different TEA and LCA studies, individually and in integrated form, using models, software, database, and simulation tools and finding key common points are essential for narrowing down the research findings so that their application can be less challenging [17]. These include the use of software from AspenTech, exclusively or in integration with other software, tools, or techniques (MATLAB, manual or excel calculations, GREET, GaBi, SimaPro, Ecoinvent, BioWin, and many more) in the comparison made from 15 to 60 studies. The comparative data between TEA and LCA and their integrated analytical study are still insufficient due to oddities in terms of compatibility with each other and with the software tools, functional units, input and output results, and unprecedented sudden situations. The introduction of mixotrophic cultures has been found to increase the overall productivity in the process of microalgal cultivation for biorefinery production. This is due to improved survival rate and stability against the sudden imbalance in pH, temperature, and other factors, multiple products, and better nutrient content utilization of wastewater and flue gases. Additionally, the integration of environmental bioremediation such as the use of wastewater, use of sewage sludge, atmospheric CO_2, and industrial flue gas, the use of natural light (sunlight) for illumination and temperature heat, alternative nutrient sources such as urea as nitrogen source, use of waste CO_2 have proven to give better output results. Cost-effective methods for cutting down the investment costs include the use of aquaculture water to lower the water consumption amount, increased oil production, increased utilization for the upgradation of biogas, and modification in cultivation techniques. The algal companies usually earn their way by selling high-value by-products from algal cultivation; e.g., astaxanthin can reduce the cost of biodiesel production from USD 3.90 to 0.54 L^{-1}, while the selling price estimation of astaxanthin synthesis is USD 200 M approx. when the production is 130 metric tons per annum [116]. Other than selling high-value compounds, algal companies usually introduce new advancements in technologies, which can be followed for better output results. Some of the new advancement methods have been filed as patents, as mentioned in Table 4.

Table 4. Patents related to new advanced methods introduced in microalgal cultivation process.

	Patent Number	Title	Earliest Priority	Publication Date	Inventor	Applicant	Reference
1.	CN114996977B	Water pollution restoration simulation method and system based on hydrodynamic coupling water quality model	3 August 2022	4 November 2022	Wei Ronglian Min Jiesheng, Zhou Lu, Wu Jianming	Zhejiang Yuansuan Technology Co ltd	[117]
2.	CN217900297U	Cooling system for producing biodiesel	26 July 2022	25 November 2022	Chen Guohong, Shen Shicong	Kunming Decheng Renewable Resources Technology Co ltd	[118]
3.	US11339360B2	Cultural systems and methods of using the same	21 July 2020	24 May 2022	Qinghua He, Jin Wang, Matthew Hilliard	Auburn University	[119]
4.	US11306264B2	Biofuel composition comprising lignin	18 February 2019	19 April 2022	Claus Felby, Stefan Mayer, Yohanna Cabrera OROZCO	Kobenhavns Universitet AP Moller Maersk AS	[120]
5.	JP7127913B2	Methods and systems for efficient bioreactor mixing and light utilization that embody low process energy and scalability	Priority claimed from US16/419,974	28 April 2022	Robert Falco	SolarClean Fuels, LLC	[121]

Table 4. *Cont.*

	Patent Number	Title	Earliest Priority	Publication Date	Inventor	Applicant	Reference
6.	CN111440727B	Screening method and application of chemical inducer for improving oil production of green algae	6 March 2020	21 October 2022	Wei Dong, Chen Junhui	The South China University of Technology SCUT	[122]
7.	KR102368058B1	Biogas purification system and purification method using the same	1 November 2021	25 February 2022	Sangjin Kim	Ecosystems Co., Ltd.	[123]
8.	CN210645948U	Heating and stirring device for biodiesel refining from illegal cooking oil	3 September 2019	2 June 2020	Hao Hailong	Yantai Grein Energy Technology Co Ltd.	[124]
9.	CN212246485U	Sewage treatment device for extracting biodiesel from illegal cooking oil	27 April 2020	29 December 2020	Xiao Lianshui	Jiangxi Guanniu Biotechnology Co ltd	[125]
10.	CN208320779U	A kind of filtering extraction element for the production of biodiesel	12 March 2018	4 January 2019	Zhao Hongfeng, Fu Xuebin, Cao Zhenhai, Chen Yuxian, Cui Wensheng, Tang Xueting, Liu Shan	Shangqiu Haotian Environmental Protection Machinery Equipment Co Ltd.	[126]
11.	CN112521988B	Biodiesel antioxidant composition and preparation method and application thereof	18 September 2019	21 October 2022	Lin Jianmin, Li Baoshi, Li Yan	Sinopec Research Institute of Petroleum Processing China Petroleum and Chemical Corp	[127]
12.	CN110964100B	Method for extracting high-purity phycocyanin and co-producing polysaccharide from spirulina	30 December 2019	14 October 2022	Ge Baosheng, Yu Qian, Yin Yonghao, Xue Mingxiong, Huang Fang, Sun Xinzu, Li Xiaonan, Tian Chen, Chen Xi	Beihai Sbd Bio Science & Technology Co ltd China University of Petroleum UPC East China	[128]

9. Conclusions

The analytical evaluation of the microalgal biorefinery production process defines it as a less cost-effective process when compared to the natural resources-based bioenergy production process. Although government initiatives and investments have provided the algal biorefineries an opportunity to withstand the market competition, their ability to stand out in the biorefinery market remains far behind the fossil fuel resource market. The necessity for evaluation of TEA and LCA of every microalgal cultivation and biomass conversion process performed should be mandatory because the main setback that microalgal companies suffer is the high production cost, which makes their market price way higher than their competing products. The data collection, interpretation, recognition of limitations and drawbacks, application of new technologies, and the overall process designing to overcome the shortcoming of the irregular factors (such as weather and contamination) can be recognized as the better strategical notion set for the process of algal cultivation for biorefinery production. The integration of environmental bioremediation procedures with microalgal cultivation and the production of biorefinery products, with cosmeceutical, nutraceutical, and pharmaceutical value, for market selling have been identified as some of the efficient methods being applied to lower the production cost and reduce negative environmental impact. The algal biorefineries have a long pathway to follow to jump over the current position of fossil fuel-based energy production, but with every initiative taken, someday, they might overturn the energy market.

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