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REVIEW

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New insights into *Chlorella vulgaris* applications

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Abstract

Environmental pollution is a big challenge that has been faced by humans in contemporary life. In this context, fossil fuel, cement production, and plastic waste pose a direct threat to the environment and biodiversity. One of the prominent solutions is the use of renewable sources, and different organisms to valorize wastes into green energy and bioplastics such as polylactic acid. *Chlorella vulgaris*, a microalgae, is a promising candidate to resolve these issues due to its ease of cultivation, fast growth, carbon dioxide uptake, and oxygen production during its growth on wastewater along with biofuels, and other productions. Thus, in this article, we focused on the potential of *Chlorella vulgaris* to be used in wastewater treatment, biohydrogen, biocement, biopolymer, food additives, and preservation, biodiesel which is seen to be the most promising for industrial scale, and related biorefineries with the most recent applications with a brief review of *Chlorella* and polylactic acid market size to realize the technical/nontechnical reasons behind the cost and obstacles that hinder the industrial production for the mentioned applications. We believe that our findings are important for those who are interested in scientific/financial research about microalgae.

KEYWORDS

biocement, biodiesel, biofuel, bioplastic, biorefinery, wastewater treatment

1 | INTRODUCTION

Fossil fuels have a significant impact on human health (Rajagopalan & Landrigan, 2021) and environmental issues, leading to nearly one in five deaths worldwide and 8.7 million premature deaths annually (Chaisson, 2021). Fuels and cooking technology pose serious health risks to 3 billion people, leading to 7 million fatalities in 2016. Heart disease, cancer, stroke, chronic illnesses, and respiratory problems are the leading causes (Sekar et al., 2021). Food production accounts for 15% of fossil fuel use (Shagun, 2023), with agriculture and food handling accounting for 21% and 49% of total US food production, respectively (Save On Energy, 2022). The pollution generated by fuels reduces photosynthesis, hindering crop growth and causing major staple crops to lose 110 million tons annually, 4% of global crop production, and potentially 15% in some regions (CCAC, 2023). Cement and plastic production are other sources that contribute to air pollution. More than 4 billion tons of cement are produced annually, contributing to about 8% of global CO_2 emissions (Chatham House, 2018) and its production is growing by 2.5% each year (Rubenstein, 2012). While 400 million tons of plastic are produced annually (IUCN, 2021), almost 12 million barrels of oil are consumed annually to produce plastic bags (Roberts, 2020). Over 99% of plastics are fossil fuel-based (CHO, 2020), with 14 million tons ending up in the ocean annually. Humans have produced 8.3 billion tons of plastic since the 1950s, with 6.3 billion tons discarded. Only 9% has been recycled and 12% incinerated, increasing production from 2

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million tons in the 1950s to 4 million tons in 2015. 79% of plastic waste is found in the natural environment, with an estimated 12 billion tons by 2050 (Mullarkey, 2017). Polymers, including fossil and bio-based plastics, are classified as biodegradable if over 60%–70% degrade within 6 months (Awaja et al., 2004). Bio-based polymers can be produced from plants (Ehman & Area, 2021), and animals (Machineni & Rao Anupoju, 2022). Despite the fact that not all bio-based plastics are biodegradable,. Approximately half of the current bio-based plastics on the market are not (Rahman & Bhoi, 2021). Microbial fermentation is a promising method for producing bio-based, degradable polymers, such as polylactic acid (PLA), by converting corn into dextrose through wet milling and fermentation (Gotro, 2012). PLA is now a commercial bioplastic made of 100% biological materials, making it suitable for mixing with microalgae (Bulota & Budtova, 2015). Polyhydroxyalkanoates (PHAs) biodegradable biopolymer can also be obtained from oiled and deoiled microalgae biomass; further, microalgae can be employed in biorefineries to reduce the cost of the processes (Chew et al., 2017), making it a sustainable technology for companies and investors since they aim for long-term profitability, continuous improvements, and market recognition (Pavolová et al., 2021). Technological shocks that are described as abrupt technological advancements that have a major impact on social, political, economic, or other outcomes play a direct role in investment as well (Akbari et al., 2021). However, the literature lacks information on recent advancements in using *Chlorella vulgaris*, microalgae known for its ease of cultivation and fast-growing features (Ma'mun et al., 2022), for biofuels, food additives correlated with health, biocement, and biopolymer production, covering technical and some financial obstacles that hinder *Chlorella vulgaris* from being utilized on industrial scales, addressing a crucial question regarding the most practical industrial application technically and economically and the future research needed to make certain applications more practical to resolve the present issues with plastic and fossil fuel usage.

2 | CHLORELLA VULGARIS

C. vulgaris is a green eukaryotic microalga of the genus *Chlorella* that has existed on Earth since the Precambrian period (Safi et al., 2014). These algae were found by Martinus Willem Beijerink in 1890 as the first microalgae with a well-defined nucleus (Beyerinick, 1890). *C. vulgaris* requires macro- and micronutrients to grow. The macronutrients involve nitrogen (N), carbon (C), and phosphorus (P) (Aguda et al., 2023), while the micronutrients involve inorganic trace elements (Hong et al., 2016). Moreover, *C. vulgaris* requires a tolerated range of temperature, light intensity, and pH with optimum values of 25–30°C (Ma et al., 2014) and 6.5–9 (Jiang et al., 2021), respectively. It has the ability to grow under 2500–1000 lux of light intensity, including a 16:8 light:dark cycle (Febrieni et al., 2020). Microalgae cultivation faces challenges such as availability of nutrients, temperature, light source, water availability, harvesting, and cost. Open-pond cultivation is not preferred over lab-scale due to the microalgal contamination risk. On the other hand, a 1-hectare lab-scale cultivation is required due to the high costs of operation, process, and maintenance (Maroušek et al., 2023). Photobioreactors (PBRs) are transparent systems that allow producers to control production conditions by separating them from the external environment. They offer higher yield without contamination risk and cost about 1.4 million USD per hectare. However, their increased building costs make them unlikely to offer a competitive advantage in lower-priced nations (Maroušek et al., 2023). Producing 1 ton of dry algae biomass was estimated to be 500 and 110 USD for the PBRs and open pond, respectively, considering the price of CO_2 capture when integrated into biomass production, which was 250 and 55 USD for the photobioreactor and open pond, respectively (Zabochnicka et al., 2022).

C. vulgaris is a spherical microscopic cell with a 5- to 10-μm diameter (Scragg et al., 2003) and has many elements similar to plants (Dvoretsky, Akulinin, et al., 2016). Its cell wall is crucial for maintaining cell integrity and providing protection against invaders and harsh environments (Safi et al., 2014). Moreover, the cell wall properties affect microalgae applications such as biodiesel production. Biodiesel can be derived from triglycerides by its conversion to biodiesel in the trans-esterification process (John Love & Bryant, 2017), and *C. vulgaris* is an attractive model for triglyceride studies due to its high triglyceride accumulation (Unterlander et al., 2017). However, its complex cell wall significantly obstructs lipid extraction (Dvoretsky, Dvoretsky, et al., 2016). Furthermore, cell wall composition is also important in bioplastic production (Rahman & Miller, 2017). Its 51–58% protein content makes it more crack-resistant and thermally stable than *Spirulina* which is utilized to blend the biomass for bioplastic formation (Zeller et al., 2013). Therefore, there were some efforts to control the protein content in *C. vulgaris* by increasing the ratio of the light intensity using red and white LED lamps (Metsoviti et al., 2020). Following the cell wall, a gel-like substance known as cytoplasm, which is composed of water, soluble proteins, and minerals that contain microalgae organelles, namely, mitochondria, chloroplast, Golgi body, vacuoles, and a nucleus, exists (Safi et al., 2014). Mitochondria and chloroplasts are crucial in microalgae growth, regulating respiration and carbon dioxide uptake, which impacts lipid, biomass, and bioactive compound productivity. Mitochondria have their own DNA for respiration (Lewin & Andersen, 2022), while chloroplasts are responsible for photosynthesis and have their own DNA as well (Safi et al., 2014). *C. vulgaris* lacks evidence of adapting to produce photosynthetic pigments to absorb light intensities (Rendón et al., 2013). Genetic engineering tools have shown promising results in improving photosynthesis, with a 1.2-fold increase in capacity and growth (Yang et al., 2017). Further study is needed to understand the function of mitochondria and chloroplasts under nuclear genome control and their own genomes for short and long-term effects.

In the early 1990s, German scientists considered *C. vulgaris* as a new food source. Japan is currently the largest consumer of *Chlorella* sp. for food (Safi et al., 2014) and medicinal purposes (Freitas, 2017).

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TABLE 1 Major contributors in the *Chlorella* sp. market worldwide (Meticulous Research, 2022).

Company	Country
Flora Manufacturing & Distributing Ltd	Canada
Roquette Klötze GmbH & Co. KG	Germany
Phycom	Netherlands
Tianjin Norland Biotech Co., Ltd.	China
Fuqing King Dnarmsa Spirulina Co. Ltd.	China
Far East Microalgae Industries, Co., Ltd. (FEMICO)	Taiwan
Allmicroalgae—Natural Products, S.A	Portugal
Qingdao Haizhijiao Biotechnology Co., Ltd.	China
STAUBER	U.S.
Alver World SA	Switzerland
AlgoSource	France
Taiwan Chlorella Manufacturing Company	Taiwan
E.I.D.—Parry	India
Dongtai City Spirulina Bio-engineering Co., Ltd.	China
Duplaco B.V.	Netherlands
Sun Chlorella Corporation	Japan
Algorigin	Switzerland
Yunnan Green A Biological Project Co., Ltd	China
Zhejiang Comp Spirulina Co., Ltd.	China
Gong Bih Enterprise Co., Ltd.	China
Wilson Group	Taiwan

Notably, the *Chlorella* sp. market started to be attractive recently. The size of the global *chlorella* sp. market was estimated at USD 275.21 million in 2021 and is anticipated to increase to USD 506.99 million by 2030, rising at a CAGR of 6.3% over the forecast period (2023–2030) from USD 292.55 million in 2022. *Chlorella* sp. application for food and beverages industry occupied the largest share in 2021, followed by personal care industry, nutraceuticals and Pharmaceuticals, and others, respectively. The demand for *Chlorella* sp. applications in medicine and personal care, is expected to increase market size in Northern America and Europe, respectively, and currently, Europe occupies 24.3% of *Chlorella* sp. market globally. In addition to that, several promising companies have stated about biodiesel production from algae which makes micro-macro algae highlighted candidates for the studies and the potential of their utilization in the fuel sector. ExxonMobil and Solix Biofuels in the USA stated about producing 1500 gallons and 5000–8000 gallons yearly, respectively (Abdo et al., 2022; ExxonMobil, 2018). Euglena Co., Ltd in Japan stated about producing 76,650 gallons (from waste cooking oil and algae) yearly (Euglena, 2018). The major contributors in the *Chlorella sp*. market worldwide are mentioned in Table 1 below (Skyquest, 2022).

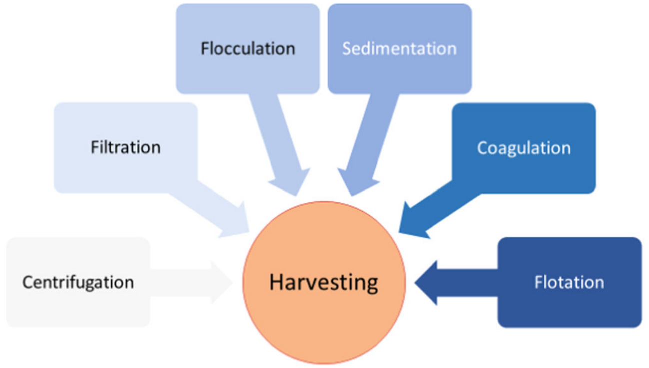

FIGURE 1 Harvesting techniques for microalgae.

3 | HARVESTING TECHNIQUES

Harvesting is an important factor in utilizing microalgae on the industrial scale because of the cost (Fasaei et al., 2018), risk of contamination (Wan et al., 2015), and effect on the final product (Hidayah Mat Yasin et al., 2019). Harvesting expenses make up about 90% of the cost of the equipment used in biomass production, and they make up about 30% of the total cost of producing microalgae (Ma et al., 2023), while harvesting of microalgae oil makes up about 60% of the produced oil (biodiesel) (Dewayanto et al., 2023). Different techniques can be used for harvesting microalgae as shown in Figure 1 below (Barros et al., 2015). Flocculation is a cost-effective, simple, and efficient method for large-scale biomass harvesting (Chozhavendhan et al., 2022). Positively charged flocculants can destabilize and neutralize the negatively charged surface of microalgae, forming flocs for harvesting (Pugazhendhi et al., 2019). Flocculation can be categorized into physical, chemical, and biological flocculation, depending on the harvested material (Branyikova et al., 2018). Chitosan, a commonly used organic polymer in *C. vulgaris* harvesting (Rashid et al., 2013), is an expensive flocculant and impractical for large-scale production due to its high cost (Yin et al., 2020). It costs 20–50 USD per kg and 7280 USD to harvest a ton of microalgae; however, it can be optimized for coating, functionalizing micro and nanospheres, and dual harvesting with additional flocculants like clay. Changing chitosan into nano-chitosan can reduce costs to $24.6 per ton, making biodiesel production economically feasible (de Morais et al., 2023). Cationic starch is also a synthetic organic polymer that can be used to harvest *C. vulgaris* (Huang et al., 2019). The acidic environment weakens electrostatic forces between microalgae and flocculates, making the process pH-dependent. The harvesting efficiency of *C. vulgaris* using cationic starch reached 99% at pH 11, with 25.74 g L^{-1} flocs concentration. The maximum biomass flocculation capacity was 8.62 g at pH 3 utilizing 1 g of starch, with self-flocculation. pH also affected the diameter of *C. vulgaris* flocs, with 0.553 mm achieved at pH 11, larger than 0.208 mm at pH 3 (Huang et al., 2019). A study suggests that the use of electrolytic microbubbles can enhance the efficiency of harvesting cationic starch for *C. vulgaris*, which is 5.5 times larger than the flocculation-settling process but requires more energy (Wei

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et al., 2020). Although cationic starch grafted tannin and nano-chitosan were documented to be very cheap, cost 27.4 and 24.6 USD per ton for microalgae harvesting, no reports of their commercial use exist (de Morais et al., 2023). Polymeric compounds can be economically feasible flocculants except forpolymeric flocculants if the ionic strength of culture suspension is high (Mathimani & Mallick, 2018). Therefore, inorganic polymers such as polyelectrolyte EM1, poly aluminum chloride, and polyacrylamide were proposed for this purpose, even though they have a risk of pollution and pH dependency (Wan et al., 2015). Metal salts like ferric sulfate, aluminum sulfate, and ferric chloride are non-polymeric chemicals used in microalgae flocculation. Aluminum sulfate is cost-effective, costs 28 USD per ton (de Morais et al., 2023), but requires high doses, potentially leading to biomass contamination with aluminum or iron (Ummalyma et al., 2016). Physical flocculation using ultrasound, electro-flocculation, and magnetic nanoparticles was also suggested to overcome the chemical drawbacks; nevertheless, some have disadvantages as well. Electro-flocculation is unsuitable for industrial scales, since electro-flocculation requires energy consumption (Fayad et al., 2017), while ultrasound is hard to apply for large scales (Bosma et al., 2003). Magnetic nanoparticles are one of the best ways to harvest microalgae due to their possibility in dustrial-scale applications and eco-friendly (Wang et al., 2015). Yet, there are recent efforts to lower the cost and energy consumption of magnetic nanoparticle synthesis and minimize the utilization of reagents during the harvesting process to make it more practical for the industrial scale. It was documented that the lowest cost is 347 USD per ton by magnetic nanoparticle fabrication and modification using arginine (de Morais et al., 2023). Coated and naked magnetic nanoparticles were compared for *C. vulgaris* harvesting, detachment, and recycling of the nanoparticles. Yttrium iron oxide ($Y_3Fe_5O_{12}$) was more efficient in terms of harvesting efficiency; it reached 90%, while naked iron oxide (Fe_3O_4) was much easier to recycle under higher pH values (Zhu et al., 2019). Diethylaminoethyl (DEAE) and polyethyleneimine (PEI) showed a high harvesting efficiency as well (>90%). While the detachment was possible only for DEAE beads (Prochazkova et al., 2013). Recent evidence stated that Fe_3O_4 nanoparticles coated with PEI had a high efficiency which was up to 99%. However, the study did not include detachment or recycling efficiency (Gerulová et al., 2022). Furthermore, microwave-synthesized naked Fe_3O_4 particles were evaluated. The particles were prepared using a rapid and low-cost method, precipitating iron sulfate using NaOH and drying in the microwave. The harvesting efficiency was over 99% at pH 3.0, and the particles could be recycled and reused at least five times. However, the detachment process involves chloroform addition (Savvidou et al., 2021), which should be replaced or avoided. Therefore, new investigations into the detachment process are required. Bio-flocculation is another way to harvest *C. vulgaris* by different techniques such as auto-flocculation by controlling pH by adding alkali or controlling the consumption of CO_2 to increase the pH which leads to the sedimentation and aggregations of microalgae (Mathimani & Mallick, 2018), although, requires alkaline addition, and involves magnesium precipitation. It is unrelated to the changes in microalgal cells, and the term "auto-flocculation" was suggested to be misleading (Vandamme et al., 2012). Microorganisms can be used as bio-flocculants as well. The harvesting efficiency was 99% and 100% by utilizing *Aspergillus fumigatus* and *Aspergillus* sp. UMN F01, respectively (Chen et al., 2018). However, the mechanism of bio-flocculation using microorganisms has not been fully defined; it is thought to be mainly a function of the reactivity of the extracellular biopolymer and/or the direct adsorption of the self-aggregating microorganisms on the target algae (Wan et al., 2015). Moreover, the high cost of bioflocculation which is 1350 USD per ton, adds another issue that should be addressed in the future and minimized to make it more practical for the scaling up.

4 | APPLICATIONS

4.1 | Bioremediation integration with biodiesel production

Bioremediation is a subfield of biotechnology that uses live organisms like bacteria and microorganisms to remove contaminants, pollutants, and toxins from soil, water, and other environments (Brown, 2022). Algae are well-known as autotrophs (organisms that utilize the energy from photosynthesis to grow), play a significant role in wastewater treatment (Amaro et al., 2023). Algae's chemical treatment capabilities through photosynthesis, can fix carbon dioxide and efficiently remove excess nutrients at a low cost. Moreover, they produce oxygen, which can mitigate the biological oxygen demand (BOD) of wastewater. Algae use waste as food and break down contaminants through enzymes, uptaking nutrients like nitrogen and phosphorus (Sahu, 2014) to grow and produce biomass, which can be utilized for different applications, including biodiesel (Anand et al., 2023). The choice of microalgae for wastewater treatment depends on the tolerance of a specific species to wastewater and its ability to grow and absorb nutrients from wastewater (Ariyanti et al., 2012). For instance, *Chlamydomonas mexicana*, *Scenedesmus obliquus*, *Chlamydomonas pitschmannii*, and *C. vulgaris* were cultivated with diazinon, and it was found that *C. vulgaris* showed better growth with a higher removal of diazinon by 94% (Kurade et al., 2016). The bioavailability of nutrients like phosphorus in wastewater is crucial for preventing phosphorus production, reducing costs. Plus, the concerning phosphorus depletion on Earth has brought attention to the bioavailability of phosphorus. Phosphorus can be available in different forms, minerals and organic. However, not all organic and mineral sources are accessible to micro-macro organisms, which must be addressed for sustainable technology (Stávková & Maroušek, 2021). *C. vulgaris* has been tested recently in integrated systems for different types of wastewater treatment with lipids investigation and biodiesel production simultaneously. When *C. vulgaris* was grown in textile wastewater (TWW), the results showed the highest growth in 50% diluted TWW reaching 11.07 $mg\,g^{-1}$ of fatty acids methyl ester; on the other hand, *C. vulgaris* could remove methylene blue from undiluted TWW up to 99%, chemical oxygen

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demand (76%), phosphorous, and nitrogen more than 80%, producing 9.12 mg g^{-1} of fatty acids methyl ester which included palmitic acid C16:0 and linolenic acid C18:3. Thus, the authors asserted that utilizing undiluted wastewater is more practical (Fazal et al., 2021).

The potential of dairy wastewater was investigated for lipid accumulation and fatty acids characterizations for biodiesel production; the authors stated that the maximum accumulation of lipids was seen in effluent with 50% dilution for initial and secondary concentration (93%, 86%) correspondingly in concentrations of 13 and 26 million cells per mL of algae, while the highest percentage of nitrate removal was 57% (Khalaji et al., 2021), and before this study, the fatty acids methyl ester in the lipids were analyzed for biodiesel production when *C. vulgaris* was cultivated and compared with *C. sorokiniana* pa.91 in non-sterilized effluent of dairy wastewater with light intensity optimization. The maximum and initial lipid content for *C. sorokiniana* pa.91 and *C. vulgaris* was 35%, 37%, and 31%, 34% at 2500 lux, respectively, and according to the amount of cetane number, the authors showed that the lipid qualities are effective for biodiesel and the fuel has a great potential even at low temperatures according to cold flow plugging properties (CFPP), and cloud point (CP) values (Asadi et al., 2020). However, the literature lacks some information about a practical extraction for lipids and biodiesel production, along with productivity and yield amounts, by utilizing dairy wastewater. Municipal and urban wastewater are not less important than dairy wastewater because they can also provide the microalgae with the required nutrients. Municipal wastewater was employed for water treatment along with CO_2 capture and biodiesel production in a coupled system to reduce the cost of the process. The maximum growth was achieved at a C/N ratio of 4 with 5% (v/v) CO_2 concentration, nitrate removal of 81%, ammonium removal of more than 99%, and phosphate removal of 88%. The obtained fatty acid methyl esters number was C16 to C18 showing the potential for biodiesel production (Ayatollahi et al., 2021). However, urban wastewater was indicated to its potential for biodiesel production when *C. vulgaris* was cultivated and the lipids formed 8% of the utilized dry biomass (3.7 g) along with nutrients removed by 87% of phosphate, 99% of ammoniacal nitrogen, and nitrate, and the authors stated that biomass is suitable to be utilized as a feedstock for biodiesel production considering the amount of the obtained fatty acid methyl esters (Ariana, 2016). Nevertheless, new investigations are required further to realize the optimization effect on the properties of the produced biodiesel and the characterization of fatty acid methyl esters because the literature lacks these data. Pilot-scale (open raceway ponds) was also investigated for swine wastewater treatment along with carbon dioxide capture for biodiesel production. At 3% CO_2, *C. vulgaris* MBFJNU-1 produced more microalgal biomass (478.5 mg L^{-1}) and total fatty acids (21%), had higher CO2 bio-fixation productivity (63.2 mg L^{-1} d^{-1}) and lipid production (9.1 mg L^{-1} d^{-1}), and nutrients removal (total phosphorus, 28%; total nitrogen, 82%; chemical oxygen demand, 37%). Additionally, enzymatic transesterification of wet biomass with 5% lipase TL and 5% phospholipase PLA resulted in the maximum biodiesel conversion (93%) (Xie et al., 2022). However, the study did not assess the biochemical makeup of microalgae cultivated in swine wastewater, a crucial factor for wastewater treatment and high-value product production simultaneously. Additionally, a border investigation is needed for pilot-scale ponds, as most studies focus on lab-scale comparisons. Scientific research is crucial for producing and utilizing biofuels at a low cost. However, the competitiveness of biofuels is also influenced by the price of fossil fuels. High fossil fuel prices make biofuels more economically viable, while a decrease may reduce their marketability. Government policies and investment can also impact the biofuel market, as increased investment in biofuel technologies can lead to higher oil prices (Vochozka, Horák, et al., 2020). The EUR/USD exchange rate is also a significant factor, as it is heavily reliant on global oil prices, which affects all markets, as many nations use these currencies as their reserve currency (Vochozka et al., 2020).

4.2 | Biohydrogen

Hydrogenase is an enzyme produced by green algae that plays an important role in anaerobic metabolism which can catalyze the reversible oxidation of molecular hydrogen (promotes the formation and utilization of hydrogen) (Wittkamp et al., 2018). This enzyme is produced by green microalgae by coupling photosynthetic electron transport chains and plastid hydrogenase [Fe-Fe] to generate hydrogen gas which differs from other enzymes produced by other microorganisms such as [Ni-Fe] hydrogenase, and nitrogenase. Hydrogenase [Fe-Fe] is more active than [Ni-Fe] hydrogenase and nitrogenase by 10–100 times and by 1000 times, respectively (Li et al., 2022), due to the existence of a distinctive active center (cluster H) (Khetkorn et al., 2017). Consequently, biohydrogen production was investigated in microalgae. *C. vulgaris* can be utilized to produce biohydrogen in many ways (direct and indirect) due to the ability of microalgae to produce hydrogenase. In a direct way, biohydrogen can be directly produced during photosynthesis from the water. However, the accumulation of the simultaneously produced oxygen inhibits hydrogenase enzymes. In an indirect way, the biomass of the microalgae can be utilized by other microorganisms by dark fermentation to produce hydrogen. The major drawback of this method is the biomass pretreatment requirement which can be done by different methods (Figure 2 below) because the hydrolytic enzymatic activity of hydrogen-producing bacteria is typically low, the pretreatment step is frequently necessary for the hydrolysis of algal biomass to release the organic materials from the algal cells and make them readily biodegradable to be utilized further in the fermentation. Thus, it is considered one of the challenges that should be handled in biohydrogen studies (Wang & Yin, 2018). Nevertheless, biorefinery employment can be more practical to reduce the cost of this process. For instance, the biomass of *C. vulgaris, Scenedesmus obliquus, and Consortium C* was converted into a carbon source for a bacterial strain, namely *Enterobacter aerogenes* by fermenting the microalgal biomass after cultivating the microalgae in urban wastewater for treatment. The sugar was accumulating after

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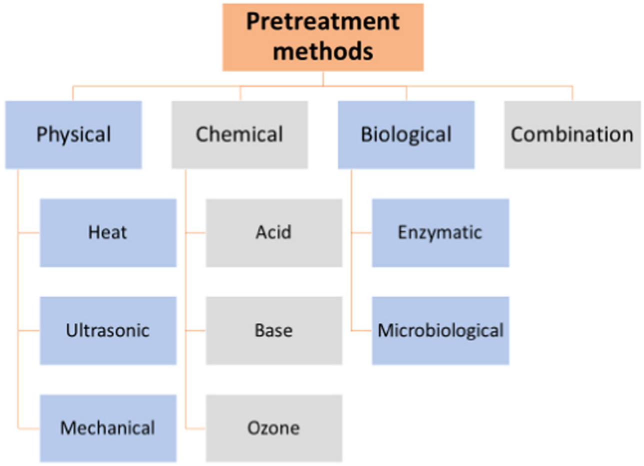

FIGURE 2 Pretreatment methods for algal biomass for biohydrogen production via the fermentation process.

reaching the status of nutritional stress in the bioreactor and afterward, the fermentation took place, and the highest yield of biohydrogen was 56.8 mL H_2/gVS by *Scenedesmus obliquus* followed by *Consortium C* and *C. vulgaris* with 46.8 mL H_2/gVS and 40.8 mL H_2/gVS, respectively, while the highest-accumulated biohydrogen production potential was for *Scenedesmus obliquus* (2.96 mL) followed by *Consortium C* and *C. vulgaris with* (2.91 mL) and (2.35 mL), respectively. Interestingly, *C. vulgaris* biomass reached a high production rate (2.9 mL h^{-1}), but due to the longer lag phase which was observed compared to other strains, the accumulated biohydrogen was lower than theirs as it was already mentioned (Batista et al., 2015). Therefore, more investigations on different composition media with different dilutions to figure out the productivity of biohydrogen of *C. vulgaris* biomass should be investigated since the culture media can affect the overall carbohydrates concentration in the biomass and eventually affect the fermentation outcome. Additionally, the pretreatment procedure for microalgae biomass might have a substantial impact on the microalgae's composition and biohydrogen output since it was investigated for *Scenedesmus obliquus*, and *Chlorella sorokiniana* which was uncovered for *C. vulgaris* (Wang & Yin, 2018). Another strategy to produce biohydrogen by *C. vulgaris* is sulfur-deprived cells because sulfur deficiency is a major factor in the cultures of microalgae that plays a role in biohydrogen production since it can inhibit protein synthesis and causes severe stress effects, leading to degradation of the photosynthetic apparatus (Nagy et al., 2018) which is known as complicated machinery that contains several complexes of protein–pigment that is involved in photosynthesis process (Rochaix, 2016), and eventually reduces the production of oxygen, which is an inhibitor of the hydrogenase enzyme (Antal & Lindblad, 2005). When immobilized-sulfur-deprived cultures of *C. vulgaris* were cultivated to produce biohydrogen, the maximum rate was 34.8 mL L^{-1} h^{-1} (Rashid et al., 2011). However, when artificial wastewater was utilized for immobilized-sulfur-deprived cultures of *C. vulgaris*, the production rate was notably decreased to 1.63 mL L^{-1} h^{-1}; nevertheless, further investigation is required because the growth conditions such as light: dark cycle, light type, and intensity were not similar (Ruiz-Marin et al., 2020). Recently, the potential of biohydrogen production by *C. vulgaris* without sulfur deficiency was also highlighted using direct photosynthesis without sulfur deficiency in the media or exposing the cells to stress conditions, and biohydrogen was obtained in the dark and light conditions average of 2.08 and 4.98 mL L^{-1} h^{-1} for the dark and light conditions, respectively. While the maximum rate reached 12 mL L^{-1} h^{-1} (Touloupakis et al., 2021). Even though hydrogen mobility is now more affordable costing 7 Euro per 100 km than traditional fossil fuels 15.6 Euro per 100 km for the first time in the European Union, hydrogen is still in its early stage in the majority of nations which impedes the advancement of hydrogen infrastructure worldwide (Maroušek et al., 2022). The low yield and high cost of biohydrogen production limit its industrial scale production and make it uncompetitive with other biofuels like biodiesel besides, the challenges including biohydrogen purification, storage, delivery, and safety, must be addressed to ensure hydrogen's viability and competitiveness (Feng et al., 2023). It has been demonstrated that nanoparticles enhance biohydrogen synthesis in microbial systems by acting as catalysts, promoting enzymatic processes that produce hydrogen (Maroušek, 2022), and enhancing the biomass productivity of the microalgae (Hidalgo et al., 2023). However, certain concentrations can be toxic. Therefore, more investigations related to optimization are required.

4.3 | *C. vulgaris* supplements and extracts for food preserving

C. vulgaris is versatile food source rich in functional macro-micro nutrients, including protein, fatty acids, and minerals (Panahi et al., 2016) and is rich in vitamins (Salvia et al., 2014) with more folate than spinach (Bito et al., 2020). The anti-lipid effects (lowering bad cholesterol and triglyceride) of *C. vulgaris* were investigated in many studies (Sherafati et al., 2022). In this regard, *C. vulgaris* powder was examined in mice, and it was observed that increases in serum and liver total cholesterol and triglycerides were significantly suppressed in the given *C. vulgaris* mice when were fed by a high-fat diet of powdered *C. vulgaris*, and there was not a significant difference in high-density lipoprotein (HDL) with no significant effect in the endogenous metabolism (Chovančíková & Šimek, 2001). On the other hand, it was indicated that the addition of *C. vulgaris* to atorvastatin treatment (reducing the body's capacity to produce cholesterol by decreasing this production) for 8 weeks of the therapy did not associate with improved control of serum lipid profiles (Panahi et al., 2012). Once, the anticancer properties of *C. vulgaris* extracts were highlighted by increasing the levels of the proteins Bax, P53, and caspase-3 while decreasing the amount of the protein Bcl-2, which causes apoptosis and DNA damage (Yusof et al., 2010), and for this reason, the function of *C. vulgaris* extracts as antioxidant and anticancer were also investigated on HeLa and DPPH cell lines. The results showed that some extracts of *C. vulgaris* exhibited more than

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50% anticancer activity and antioxidant activity against Hela cancer cell lines (El-fayoumy et al., 2021). Furthermore, water extracts from *Spirulina platensis* and *C. vulgaris* showed prolonged characteristics of packaged sardine fish when they were investigated due to the availability of mineral content and bioactive chemical components. The extracts prolonged the shelf life of sardine for 3 days. However, the utilization of water extracts from *S. platensis* was preferred over the extracts of *C. vulgaris*. Nevertheless, both extracts can be used as antimicrobial and antioxidant additives to preserve sardine fish because these extracts inhibit the growth of lactic acid bacteria, while *C. vulgaris* extract was a stronger inhibitory on tyramine accumulation, with 2- to 4-fold lower tyramine accumulation in sardine meat than *S. platensis* extract. Also, the authors indicated that *C. vulgaris* extract was more effective in the inhibition of ammonia production and the most toxic biogenic amines such as tyramine and histamine in fish meat (Özogul et al., 2021). However, the impact of the extracts on the accumulation of biogenic amines was different, depending on storage time and amine type (Özogul et al., 2021). Additionally, the carotenoid in *C. vulgaris* extracts, in particular, can be used to make bio-based plastic for food packaging. Lutein, α-carotene, and β-carotene were isolated from *C. vulgaris*, and it was demonstrated that the addition of carotenoids to chitosan film considerably enhanced the film and demonstrated its suitability for use as a packaging material due to its antioxidative qualities (Şahin et al., 2019). Hence, new investigations in terms of utilization of *C. vulgaris* extracts in bio-based plastic are needed and how the extracts affect the mechanical and thermal properties of the bioplastics along with their effects on the shelf life of the packed products if they were used for packaging. Utilization the whole microalgae for food sector is commercially available and the most reasonable application of Chlorella sp. because the process is faster and easier than others which minimizes the overall cost (Enzing et al., 2014). However, consumer demand significantly affects its market, and Spirulina dominates the market since 12,000 tons is produced yearly, while only 5000 tons is produced from *Chlorella* (Rani et al., 2018). Probably, understanding certain extracts from *Chlorella* that *Spirulina* does not or poorly have and correlating these extracts with health-boosting might raise *Chlorella*'s market. The literature lacks information about the integration of a specific extract production with other productions since this process can reduce the overall cost leading to a better feasibility to produce an extract in industrial scale.

4.4 | Biocement

Biocement is a product innovation in the development of a bioprocess technology called Biocementing or Biocementation. Biocement refers to calcium carbonate ($CaCO_3$) deposits formed as a result of microbial activity in the systems that contain rich supplements in calcium ions. The major role of microorganisms in the precipitation of carbonate is due to their capability to produce an alkaline environment by many physiological actions (Ariyanti, 2012). The effects of different nitrogen sources and different concentrations of sodium bicarbonate and carbon dioxide were investigated on *C. vulgaris* in terms of biomass concentration, biocement sedimentation rate, and productivity. According to the results, nitrate was favored over urea and ammonium, while the biocement efficiency was 90% and the biomass productivity was 490 mg L^{-1} when calcium chloride (0.4 g L^{-1}), sodium bicarbonate (2.5 g L^{-1}), and sodium nitrate (1 g L^{-1}) were applied in the growth medium at the recommended proportions (Arabian, 2022). Further, the biomineralization capability of different species of microalgae in calcification media that contained sodium bicarbonate and calcium chloride dehydrate was investigated. Among the eight microalgae that have been examined, *Synechocystis* sp. had the highest calcium ion removal rate (0.70 mM day^{-1}), followed by *C. vulgaris* (0.40 mM day^{-1}) (Kavithraashree et al., 2022).

Calcium precipitation and *C. vulgaris* harvesting by flocculation showed a significant correlation. When the pH of the medium was adjusted to 11 for *C. vulgaris* harvesting, it was noticed that both calcium and magnesium were precipitated, and these precipitates can be utilized for further applications (Vandamme et al., 2012). Hence, the issue of pH dependency in microalgae harvesting (flocculation) can be employed or "invested" for biocement production or other applications related to calcium and/or magnesium. From what has been mentioned above, it can be considered that *C. vulgaris* as a promising candidate in civil engineering as well, and it would be more practical to treat wastewater that contains calcium ions and eventually utilize the biomass for different products, as mentioned previously. Prometheus Materials Inc. has unleashed the production of biocement from biomineralizing (the method through which living things' matrix absorbs mineral crystals) cyanobacteria and it was claimed that this cement is an alternative to Portland cement (Dreith, 2022). Biocement mortars have a 90% lower thermal conductivity compared to conventional mortars, resulting in higher energy efficiency in buildings, reducing lifetime costs and CO_2 emissions associated with heating and cooling (Edwards, 2022). Pyrolysis of the biomass was also suggested to improve the efficiency, and the addition of certain salts was suggested to be commercially beneficial (Maroušek et al., 2023). Yet, the optimization and biocement production by *C. vulgaris* needs to be investigated further in terms of calcium carbonate precipitation, the addition of the biomass effect into the produced biocement, and producing biocement by charring the biomass before and after oil extraction in two steps of biocement–biodiesel production. Finally, the price of the process must be investigated due to the lack of information

4.5 | Biodegradable bioplastics

4.5.1 | Polyhydroxyalkanoates

PHAs are biodegradable polyesters produced by bacteria (Kourmentza et al., 2017), microalgae (Costa et al., 2019), cyanobacteria (Afreen et al., 2021), and genetically engineered yeast (Gao et al., 2015). They serve as carbon and energy storage without toxic

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waste (Amstutz et al., 2019) and are fully recyclable. PHAs can be produced from various feedstocks, including wastes (Li & Wilkins, 2020). However, microalgal biomass is considered the best due to its lower cost (Rahman et al., 2014). *Chlorella fusca* (Cassuriaga et al., 2018), *Chlorella pyrenoidosa* (Das et al., 2018), *Tetradesmus obliquus* (Páblo Eugênio da Costa e & Laureen Michelle, 2022), *Synechococcus subsalsus* and *Spirulina* sp. (Costa et al., 2018) were reported for PHAs production, and it relays on the growth conditions, utilized media, CO_2 concentration, and nitrogen and phosphorus deficiency. For example, PHAs were produced by *Synechococcus elongates*; the production was 17% and 7% (w/w dry biomass) with nitrogen and phosphorus deficiency, respectively (Mendhulkar & Shetye, 2017). *Nostoc muscorum* was also investigated under different growth conditions; PHAs production was 69% under phosphorus deficiency (Bhati & Mallick, 2015) and 31% (w/w dry biomass) with acetate and propionate addition (Mallick et al., 2007). It was shown that *C. vulgaris* has the potential to produce PHAs by utilizing agro-industry residue corn steep liquor (Páblo Eugênio da Costa e & Laureen Michelle, 2022). However, there is neither data about the exact concentration and productivity nor yield of PHAs. The most recent trend in PHA production by *Chlorella* sp. is the utilization of de-oiled or de-fatted biomass in the fermentation process to obtain the PHAs by microorganisms. *Paracoccus* sp. LL1 was employed to ferment glucose and *Chlorella* biomass to compare the produced PHAs along with carotenoids. Impressively, the obtained concentrations of PHAs and carotenoids were higher when the biomass was fermented; the concentrations that were obtained from biomass and sugar fermentation were 3.62 g L^{-1} PHAs and 11.7 mg L^{-1} carotenoids and 1.48 g L^{-1} PHAs and 6.08 mg L^{-1} carotenoids, respectively (Khomlaem et al., 2020). Moreover, the production of PHAs was improved when *Chlorella* biomass was fermented by *Cupriavidus necator* KCTC 2649, and *Haloferax mediterranei* DSM 1411. The highest PHAs production was found in *C. necator* KCTC 2649 with 7.51 ± 0.20 g L^{-1}, 75% of dry cell weight, followed by 3.79 ± 0.03 g L^{-1}, 56% of dry cell weight in *H. mediterranei* DSM 1411. However, the carotenoids amount was decreased, and the maximum carotenoid content was 1.80 ± 0.16 mg L^{-1} produced by *H. mediterranei* DSM 1411 (Khomlaem et al., 2021). Despite the data available about de-oiled biomass utilization to produce PHAs, the literature still lacks critical information about specifying the strain of *Chlorella* that has been grown to produce the biomass because the composition of the biomass is different. Moreover, specifying the strain of microalgae will be useful in biorefinery applications according to the desired final product such as biodiesel-PHAs-wastewater treatment simultaneously.

Polyhydroxybutyrate (PHB) is another polyester that belongs to the PHAs family and is produced by bacteria (McAdam et al., 2020) and microalgae (Robert & Iyer, 2018a). However, PHA has better chemical and physical properties and is comparable to petroleum-based plastics, whereas PHB has less elasticity, is very brittle, and its thermal properties are unsuitable for rigid products (Singh et al., 2015). PHB is a cost-effective, eco-friendly thermoplastic with similar properties to commercial polypropylene. It is less flexible than traditional plastics and is completely biodegradable. PHB can be produced using algae, offering economic efficiency and low costs. Many microalgae species were investigated for PHB production; for instance, the maximum yield of PHB was 30% from 0.94 g L^{-1} of *C. sorokiniana* biomass (Kumari et al., 2022), while it was up to 145.1 mg L^{-1} (17% of cell dry weight) under phosphate deficiency and limited CO_2 supply using *N. muscorum* (Haase et al., 2012). Moreover, *Spirulina* sp. was described as a good candidate for PHB production; the yield was 21% of the cell dry weight in 15 days (Martins et al., 2017). Recently, PHB was detected in *C. vulgaris* by its extraction from the biomass using hot chloroform (Robert & Iyer, 2018) and it was quantified in a different study from 0.6 g of *C. vulgaris* biomass using mechanical (sonication) and chemical (NaClO) cell disruption methods, and the best yield was 37% (Setyorini & Dianursanti, 2021). Furthermore, *C. vulgaris* can be utilized in multiple production processes to make the process more sustainable and economical by utilizing the algal biomass completely without any production of algal waste. Recently, *C. vulgaris* was utilized to produce biodiesel and PHB by using a biorefinery; the microalgae were cultivated in wastewater, which makes the process more economical and sustainable by utilizing the algal biomass completely and without the production of any waste or residues. The authors utilized the biomass to extract the oil and then the de-oiled biomass to produce PHB. The maximum lipid and PHB yield were 28 wt%, and 0.41 g g^{-1}, respectively (Arun et al., 2022).

4.5.2 | Polylactic acid

PLA, an FDA-approved thermoplastic monomer (Pines et al., 2008), is widely used in food handling (Marano et al., 2022), 3D printing (Marșavina et al., 2022) and promising for 4D printing (Lin et al., 2022) and medical applications (Schätzlein et al., 2022). PLA is not toxic in solid form nor carcinogenic in the human body (Rogers, 2015). When introduced into the human body, PLA hydrolyzes to alpha-hydroxy acid then processed into the tricarboxylic acid cycle and excreted (Konta et al., 2017). However, PLA can be toxic, if it is inhaled or absorbed into the skin or eyes as a vapor or liquid (Rogers, 2015). PLA can be derived from renewable sources like corn starch (Rogers, 2015), different microorganisms (Mehmood et al., 2023) including microalgae (Bussa et al., 2019). The free-lipid biomass from *Nannochloropsis salina* was utilized as a feedstock for *Lactobacillus pentosus* in fermentation process to produce lactic acid, and the results showed that lactic acid yield was 93% from 3 to 25 g L^{-1} sugar (Talukder et al., 2012). In addition to that, lactic acid production by microalgal biomass fermentation was indicated to be practical on large scales when lactic acid was produced by *Hydrodictyon reticulum* fermentation which was carried out by *Lactobacillus paracasei* LA104. With a final concentration of 37.11 g L^{-1} and a productivity of 1.03 g L^{-1} h^{-}, the yield was 46 g/100 g *H. Reticulum* dry material (Nguyen et al., 2012). The potential of *C. vulgaris* to be utilized as a feedstock for fermentation was also studied. The results showed that *C. vulgaris* biomass contains a high source of carbohydrates, which

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can be utilized for lactic acid production (Agwa et al., 2022). Furthermore, it was noticed that *C. vulgaris* could change the enzymatic activity of *Lactobacillus* sp. When they were cocultured. The results showed higher production of L-lactic acid and lower D-lactic acid production, and this characteristic could be used to determine the final product (Ścieszka & Klewicka, 2020). However, more studies are required to understand the yield and productivity. The degradation rate of PLA depends on factors such as molecular weight, crystallinity, and stereochemistry (Tokiwa & Calabia, 2006). Thermal degradation, which occurs when 5% of the polymer is lost at 325°C and leaves no residue at 500°C (Sin et al., 2013), is not eco-friendly due to the emission of volatile compounds (Wojtyła et al., 2017). Enzymatic degradation, which takes several weeks to 24 months, is also possible by enzymes found in microorganisms such as protease (Seok et al., 2022), lipase (Satti et al., 2019), esterase (Mistry et al., 2022), and cutinase-like enzyme (Masaki et al., 2005), whereas other types of plastics take approximately 500 years (Kaushal et al., 2021). The rate of degradation is influenced by the polymer's structure and composition as well. D-PLA degrading faster than L-PLA (da Silva et al., 2018) and the addition of algal biomass to PLA accelerates the biodegradation of PLA-based polymers (Kalita et al., 2021). However, there is no characterization of PLA/*C. vulgaris* in terms of biopolymer optimization and biodegradation analysis.

4.5.3 | PLA market size and share

PLA is relatively inexpensive when compared to other types of biodegradable bioplastics and has various mechanical advantages over others, making it a popular material. In 2019, the production capacity of PLA was around 290,000 tons (Fortune Business Insights, 2021), and the global PLA market value was USD 1 billion in 2021 growing at CAGR of 12% from 2021 to 2026 (Markets and Markets, 2022), and expected to reach USD 2,306,708.2 thousand by 2028 (Fortune Business Insights, 2021). In 2020, biodegradable plastics occupied 58% of the total plastic production globally, and among them, PLA had the largest share since its production capacity reached 19% and is expected to be 20% in 2025 from the total capacity of biodegradable plastic which is estimated to be 63% from plastic production (De Guzman, 2020). NatureWorks is the first company and the largest that produces PLA on a commercial scale in the world; it started in 2002, and in 2013, expanded its business and started to produce 150,000 metric tons annually. Furthermore, it has constructed a new facility in Thailand and is expected to be open in 2024; the facility will have an annual capacity of 75,000 tons of Ingeo® biopolymer (NatureWorks, 2021). In line with NatureWorks company, Futerro also plans to set up an integrated factory in France to produce and recycle PLA with 75,000-ton capacity as an annual production (Futerro, 2022). Some companies that produce PLA are mentioned in Table 2 below. Packaging is the main application of PLA for consumer-packaged goods, food service, and supermarket packaging. According to European Bioplastic, packaging accounted for 59% of biodegradable plastics produced in 2019. A fraction of this represents 0.5% of the total plastic packaging produced in biodegradable packaging. By the end of 2017, 164,000 biodegradable tons of packaging for food and food items were produced (Jia, 2020). China is considered the largest PLA consumer, and it is expected to remain the world's largest PLA consumer over 2020-2035, driven by new domestic capacity addition in the country, and also export demands (NexanTECA, 2021).

TABLE 2 A list of PLA products by different companies.

Company	Brand/trade name	Country	Product	References
RTP Company, Inc.	RTP-PLA compounds	USA	Covers, toys, medical devices, furniture	Renewable Carbon News (2012)
FkuR Kunststoff GmbH	Bio-Flex®	Germany	Packaging	Chinh and Hoang (2022)
NatureWorks® LLC	Ingeo™	USA. Thailand	Ingeo fibers for medical applications, agriculture, packaging, household, construction, electronics, and 3D printing	Maazouz and Lamnawar (2011); NatureWorks (2023)
UNITIKA Plastics Division	TERRAMAC	Japan	Shock absorbance materials like containers	Sudesh and Iwata (2008)
Kanebo Gohsen Ltd.	Lactron®	Japan	fabric	Sudesh and Iwata (2008)
NaturePLAST	Natureplast PLE 005	France	rubber	Agrobiobase (2013)
			Flexible packaging: film, textile fiber	
NaturePLAST	n.d.	France	Heat-resistant PLA resins	Guzman (2015)
Hycail bv	HYCAIL®	Netherlands	n.d.	Kowalczyk et al. (2011)
Kareline Oy Ltd.	Kareline®	Finland	Fiber-reinforced, thermoplastic composite	MaterialDistrict (2009)
FUTERRO	n.d.	Belgium	Food packaging, films, foams, textile fibers, 3D filaments, cases	Bioplastics Magazine (2020)

Abbreviations: n.d., referring to no data; PLA, polylactic acid.

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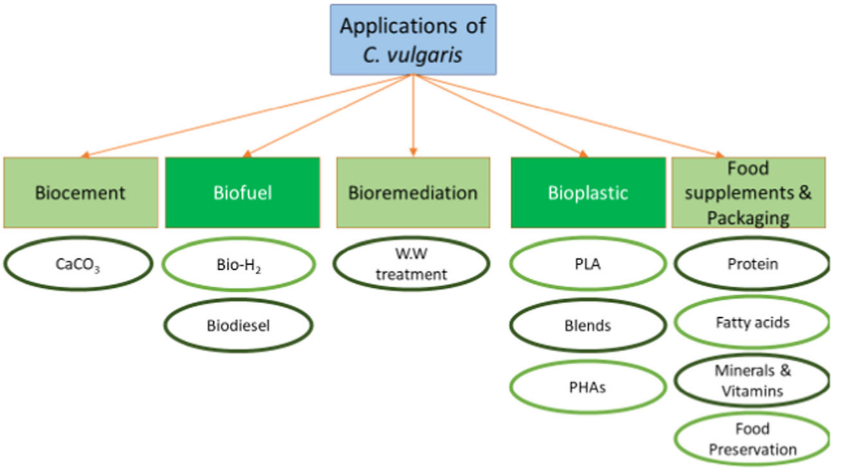

FIGURE 3 *Chlorella vulgaris* applications. Bio-H_2, bio-hydrogen; $CaCO_3$, Calcium carbonate; PHA, polyhydroxyalkanoate; PLA, polylactic acid; W.W, wastewater.

4.5.4 | Plastic blends

Microalgae-produced bioplastics have similar properties to petroleum-based plastics, making them suitable for existing applications. They are biodegradable, making them eco-friendly (Rahman & Miller, 2017). *Chlorella* sp. Can be utilized to produce bioplastic because they have a high breaking strength due to their dense cell wall and high thermal stability (Cinar et al., 2020). Both compatibilizer and biomass treatment are effective for *Chlorella*-based plastics. When the homogenizer was used for *Chlorella* powder treatment before mixing it with PVA, the results indicated that the treatment improved the tensile strength and elongation by 15.3 kgf/cm^2 and 100%, respectively (Sabathini et al., 2018). Maleic anhydrates (MAs) compatibilizer showed tensile strength, elongation, elasticity, and homogeneity improvements, when it was incorporated with PVA-*Chlorella* plastic-based (Dianursanti & Khalis, 2018). Another composition was synthesized by blending *Chlorella* sp. with polyethylene (PE) through chemical modification of PE with MA. The result showed improved tensile strength by 40 wt % (Otsuki et al., 2004). However, PE is not biodegradable. Therefore, biodegradable bioplastics like PLA are preferred. Although PLA has many benefits, as previously discussed, it also has significant disadvantages, including brittleness and low tear resistance (Kim et al., 2020). Therefore, there were many efforts including the incorporation of PLA with other plastics (Pivsa-Art et al., 2016), plant biomass (Yoksan et al., 2022), or algal biomass (Liao et al., 2023) to improve the mechanical and thermal properties. Duckweed plant was incorporated with PLA/thermoplastic cassava starch (PLA/TPS) blend and the results showed improved Young's modulus, hardness, and tensile strength (Yoksan et al., 2022). PLA/algae blend was also investigated, and the results showed improved Young's modulus when macroalgae were incorporated with PLA. However, the strain and the tensile strength were decreased (Bulota & Budtova, 2015). Furthermore, cell disruption effect microalgae, namely *spirulina* sp. Blend with PLA was investigated as well, and it was demonstrated that the tensile strength was increased by 25% compared to raw *spirulina* (Liao et al., 2023). Therefore, new investigations are required in terms of PLA/*C. vulgaris* blend along with chemical composition analysis and biomass treatment impact the mechanical, thermal, and degradation properties of the biopolymer (bio-blend) since *C. vulgaris* was indicated for biorefinery application which leads to an economical process. Finally, a summary of overall *C. vulgaris* applications is mentioned in Figure 3.

The process of producing bioplastics is expensive and, being a relatively new technology, less competitive than that of fossil-based plastics (Shah & Gangadeen, 2023). That being said, given a stable price for fossil fuel, the price gap is anticipated to close considerably by 2030, considering a stable price of fossil fuel, and the price of fossil-based plastics will be higher in a case of higher fossil fuel costs (Horvat et al., 2018).

5 | CONCLUSION

C. vulgaris, easily cultivated and isolated from various sources, is a promising candidate for various bioprocesses and food supplements. Studying its unique extracts and their potential impact on human health could potentially boost its market, as consumer recognition directly influences its growth. Biodiesel production in industrial scale is the most feasible application, but several techno-economic bottlenecks hinder its commercialization. These bottlenecks are linked to algae production and require processing as a side branch of a complex biorefinery process. Nontechnical factors like global fossil fuel costs, exchange rates, investor decisions, and governmental policies also affect biodiesel production and price, necessitating addressing these to improve green energy production. *C. vulgaris* has the potential for biohydrogen and biocement production; however, challenges related to hydrogen safety, operational cost, storage, and delivery hinder scaling. However, biocement and biomineralizing processes involving biomass and other biomaterials have not been extensively investigated. Microalgae-based polymers are uncompetitive with fossil-based. Probably, by valorization of de-oiled biomass for biopolymer will be more practical if it is produced as a byproduct of other applications.

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AUTHOR CONTRIBUTIONS

Mohammed Al-Hammadi: Completed the literature review, analyzed the data, and wrote the manuscript. Mine Güngörmüşler: Designed and supervised the content and revised the manuscript. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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