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Review

Microalgae-derived biolubricants: Challenges and opportunities

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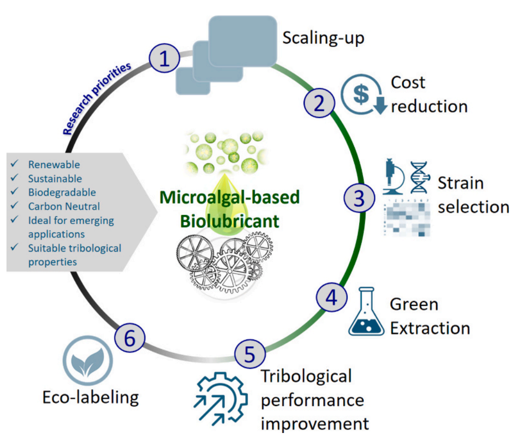
HIGHLIGHTS

- Microalgae-derived biolubricants are attractive for new and emerging applications.
- Production scale and harvesting cost must be overcome for commercial realisation.
- Technologies are available to extract lipid and convert to biolubricants at scale.
- Polysaccharide biolubricants have significant and unexplored potential.
- International standard for biolubricant labeling is vital for market development.

GRAPHICAL ABSTRACT



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ABSTRACT

Lubricants are indispensable in the modern economy for controlling friction and wear across many industries. Traditional lubricants are derived from petroleum crude and can cause significant ecological impact if released into the environment. Microalgae have emerged as a potential alternative to petroleum crude for producing renewable and environmentally friendly biolubricants. This review systematically assesses recent developments in microalgal-based biolubricant production, including tribological performance, microalgae selection, cultivation, harvesting, lipid and polysaccharide extraction and conversion to biolubricants, and market development. Compared to petroleum-based lubricants in terms of tribological properties, biolubricants are compatible with most emerging applications, such as electric vehicles and wind turbines. Nevertheless, they are less thermally and chemically stable, thus, may not be suitable for some traditional applications such as internal combustion engines. Literature data corroborated in this study reveals an urgent need for further research to scale up microalgae production and lower the cost of biomass harvesting. While technologies for converting microalgae-derived lipids to biolubricants appear to be well established, additional work is necessary to also utilize polysaccharides as another key ingredient for producing biolubricants, especially for low-temperature applications. Extraction methods are well established but further research is also needed to reduce the ecological impact, especially to

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utilize green solvents and reduce solvent consumption. Additionally, future research should delve into the use of nanoparticles as effective additives to obtain microalgae-based biolubricants with superior properties. Finally, it is essential to standardize the labeling system of biolubricants to establish a global market.

1. Introduction

Lubricants are substances to reduce friction and wear between moving surfaces in various systems. By forming a protective film, they facilitate smoother operation and prevent direct metal-to-metal contact, thereby extending the lifespan of components and improving efficiency. Lubricants come in diverse forms, including oils, greases, and solid lubricants, each tailored to specific applications ranging from automotive engines to industrial machinery. Their primary function lies in enhancing performance by minimizing frictional losses and heat generation, ensuring optimal functioning and reliability of mechanical systems.

The rapid expansion of industrialization and manufacturing activities worldwide has led to a significant increase in the demand for lubricants. As industries become more advanced and machinery more complex, there is a corresponding rise in the standards for lubricants. Modern applications demand products that not only enhance performance but also meet stringent requirements for environmental impact, safety, and operational efficiency. This dual pressure of increased demand and higher standards is driving innovation in lubricant formulations towards more sustainable solutions.

Given the critical role of lubricants, the sector has significant inertia and petroleum-based lubricants still dominate the current market (Matiliunaite and Paulauskiene, 2018). Petroleum-based lubricants are toxic, non-biodegradable, and contribute significantly to greenhouse gas emissions throughout their lifecycle from production to disposal. As a finite resource, the depletion of petroleum reserves raises concerns about long-term sustainability and the economic viability of continued exploitation. Additionally, petroleum-based lubricants can be less reliable under extreme conditions, such as high temperatures and pressures, compared to synthetic alternatives (Kallas et al., 2024). These problems highlight the urgent need for developing and adopting sustainable lubricants to reduce dependence on petroleum while improving performance standards.

Biolubricants offer a sustainable and effective alternative to petroleum-based lubricants (Kurre and Yadav, 2023). Synthesized from diverse renewable sources such as vegetable oils, animal fats, waste cooking oil, and microalgal, biolubricants are renewable, sustainable, and biodegradable fuels with low greenhouse gas emissions (Khan et al., 2022; Mendes et al., 2022). In addition, biolubricants also exhibit comparable or superior performance characteristics in comparison to petroleum-based lubricants (Narayana Sarma and Vinu, 2022). Biolubricants possess tribological and physicochemical properties such as increased lubricity, high viscosity index, high thermal stability, and high flash point. However, biolubricants also have certain disadvantages, such as poor oxidative stability at high temperatures.

As the world continues to grapple with the environmental impacts of fossil fuels, the search for renewable and eco-friendly resources has become paramount. Photosynthetic microorganisms, particularly microalgal, are being explored as ideal feedstocks for synthesizing biolubricants and achieving carbon neutrality. Some microalgal strains have high photosynthetic efficiencies and the ability to accumulate high levels of lipids and carbohydrates in their cells (Zhu et al., 2022). Microalgal cultivation does not require arable land or fresh water and can be carried out in diverse environments including sea and wastewater (Javed et al., 2019). Biolubricants derived from microalgal demonstrated good tribological properties. Several preliminary researches demonstrate that microalgal-based biolubricants exhibit favorable properties such as high thermal stability, biodegradability, and potential applications in reducing friction and wear in various industrial and automotive sectors (Cheah et al., 2020; Patel et al., 2021).

The majority of studies have focused on microalgal for biofuel rather than exploring their viability as biolubricants. Existing research often emphasizes the technical feasibility of microalgal biomass production, extraction, or conversion into biolubricants, but a comprehensive assessment of the entire process is scarce. There have been no previous attempts to comprehensively summarise key challenges and outline a roadmap for microalgal-based biolubricants. This makes it difficult to determine the true potential of microalgal biolubricants in commercial applications.

This review aims to examine the current state of research in the field of biolubricant production from microalgal. The evolution of biolubricants from laboratory discovery to current commercial status is presented. The key steps of the microalgal-based biolubricant supply chain cycle are illustrated, from biomass production, extraction and conversion into biolubricants to tribological performance assessment and market development. Each subset of this supply cycle is analyzed and assessed from both technical and economic perspectives. The review also describes the pathway to synthesize biolubricants from two important components of microalgal cells: lipids and polysaccharides, with synthesis from polysaccharides yet to be achieved. A systematic analysis of all peer-reviewed literature on microalgal-based biolubricants is conducted to identify significant knowledge gaps.

2. Biolubricants

2.1. Lubricants

Lubricants are indispensable in the modern society and play an important role in many aspects of our daily lives. In mechanical devices, lubricants reduce friction and wear between surfaces of mutual contact. Lubricants ensure reliable, durable, smooth, and energy-efficient operations of tools and equipment. In a well-lubricated device, friction can be eliminated or substantially reduced, resulting in less energy consumption and emissions. Lubricants also provide additional benefits such as corrosion inhibition and cooling.

As the world economy has grown significantly over the last few decades, the demand for lubricants has also grown. In 2019, the global demand for lubricants was about 37 million tons (Petroleum and Refinery, 2023). This is equivalent to an average annual consumption of 6 kg of lubricants per person.

Lubricant performance can be assessed by a range of parameters. Viscosity is arguably the most important tribological property as it is directly related to the reduction of friction and wear resistance. Other parameters such as oxidation and thermal stability, density, flash point, and pour point are also important as they dictate lubricant performance in each practical and specific use.

The production, usage, and disposal of conventional lubricants are unsustainable. Conventional lubricants typically contain over 90 % distilled hydrocarbons from crude oil or other forms of fossil fuel. There is an inherent supply risk when fossil fuels are depleted. Fossil fuel extraction and conversion to lubricant are also associated with significant greenhouse gas emissions.

Water and soil contamination by lubricating oil is a major threat to the environment. Each year over 20 million tons of lubricating oils are released into the environment from operational discharges and leaks (Syahir et al., 2017). Lubricant spills into environmental water can form a thin film at the surface to prevent oxygen exchange between water and the atmosphere, causing deprivation or hypoxia in fish and other aquatic organisms (Ossai et al., 2020). Land based lubricant pollution can drastically alter soil's physicochemical characteristics such as reducing soil moisture and nutrient exchange capacity. Petroleum-based lubricants contain many substances that are toxic to humans, animals, soil organisms, and plants (Nowak et al., 2019). Given the several drawbacks of petroleum-based lubricants, biolubricants have recently emerged as a promising alternative.

2.2. Biolubricant

Biolubricants are lubricants derived from plants, animals, and any microorganisms with high lipid or carbohydrate content (Barbera et al., 2022; Borah et al., 2021). Thus, they are renewable, more biodegradable, less toxic, and associated with lower greenhouse gas emissions in comparison to petroleum-based lubricants (Farfan et al., 2022; Mobarak et al., 2014). Biolubricants have been commercially produced and used at scale in recent years (Kurre and Yadav, 2023).

Transesterification and esterification are two main chemical processes for biolubricant production from lipid. In the transesterification process, triglycerides in plant or animal-based feedstocks react with an alcohol in the presence of a catalyst to produce fatty acid methyl ester (FAME). FAME is then esterified again with alcohols to form stable esters that can be used as biolubricants. Carbohydrates, particularly polysaccharides, can also be extracted and directly utilized as biolubricants due to their inherent lubricating properties.

In the context of biolubricant production, esterification can be tuned for desirable lubricant properties. Biolubricants are comparable to petroleum-based lubricants in several key tribological properties including viscosity index, flash point, pour point, and thermal stability (Table 1). The density of biolubricants ranges from 0.8 to 0.9 g cm^{-3}, similar to petroleum-based lubricants.

Viscosity is critical to lubricant performance. Viscosity is a measure of resistance to flow. In general, viscosity decreases when the temperature increases. Viscosity is directly related to friction reduction, thus, lubricants with suitable viscosity can significantly improve equipment performance and service life. In general, the viscosity of petroleum-based lubricants is higher than that of biolubricants (Table 1). At 40 °C, viscosity of most petroleum-based lubricants is over 100 $mm^2\ s^{-1}$ with ISO VG 32 being the only exception. ISO VG 32 is, however, used predominantly as a hydraulic oil rather than a traditional lubricant. By contrast, biolubricants tend to have much lower viscosity, in a range of 5.7–105 $mm^2\ s^{-1}$, except for castor oil. At 100 °C, the difference in viscosity between petroleum-based and biolubricants becomes less apparent (Table 1).

Viscosity index indicates the changes of viscosity with temperature. High viscosity index indicates a smaller change in viscosity with temperature. For machines and equipment working in a wide range of temperatures, it is desirable to use lubricant with a high viscosity index. In general, biolubricants possess a higher viscosity index than petroleum-based lubricants (Table 1). While the viscosity index of petroleum-based lubricants is about 100, most biolubricants have higher viscosity index values (>160).

Flash point is also an important lubricant property. The flash point describes the lowest ignition temperature of lubricant. First and foremost, the flash point is an important safety consideration. Overall, the flash point of petroleum-based lubricants is lower than that of biolubricant (Table 1). Thus, biolubricants are a better alternative in terms of safety compared to petroleum-based lubricants.

The pour point is the lowest temperature at which the lubricant can still flow. Biolubricants produced from coconut, sunflower, castor and jatropha present lower pour points (Table 1). Low pour point allows

Table 1
Physicochemical properties of petroleum-based lubricants and biolubricants.

	Lubricant type or biomass source	Density (g cm^{-3})	Viscosity ($mm^2\ s^{-1}$ at 40 °C)	Viscosity ($mm^2\ s^{-1}$ at 100 °C)	Viscosity index	Pour point (°C)	Flash point (°C)	Thermal stability (°C)	Oxidation stability (h at 110 °C)	Acid value (mg KOH g^{-1})	Refs.
Lubricants	SAE20W40	0.879	103	16	148	−21	200	198	–	0.84	[1]
	ISO VG32	0.868	32	6	108	−6	204	–	–	–	[2]
	AG100	–	216	20	103	−18	244	–	–	–	[3]
	Liquid paraffin	0.880	100	–	98	−15	210	–	–	0.01	[4]
Biolubricants	Coconut	0.882	105	13	116	−18	225	257	35.4	0.40	[5]
	Soybean	0.921	67	9	105	−6	158	310	2.1	–	[6]
	Olive	0.917	37	8	186	−3	188	390	6.6	6.40	[7]
	Palm	0.894	42	9	194	7	250	273	13.5	0.40	[8]
	Sunflower	0.934	28	6	176	−18	332	276	0.9	4.00	[9]
	Castor	0.959	250	19	88	−36	245	–	–	0.91	[10]
	Jatropha	0.917	37	9	164	−23	273	–	2.3	4.65	[11]
	Fish	0.930	23	6	211	−6	204	–	–	–	[12]
	Chicken	0.876	5.7	–	–	–	163	–	–	0.31	[13]
	Lard	–	38	9	235	−11	–	–	–	0.68	[14]
	Waste oil	0.895	75	36	466	−13	235	–	–	–	[15]
	Microalgae	0.970–1.040	71–74	9	180	−6	248	350	*	22.90	[16]

[1]: (Choudhury et al., 2021; Kalam et al., 2017).
[2]: (Cecilia et al., 2020; Milčić et al., 2021; Wang et al., 2014).
[3]: (Cecilia et al., 2020).
[4]: (Hu et al., 2013).
[5]: (Ahmed et al., 2020; Neha Deepak and Nathi Ram, 2021).
[6]: (Parente et al., 2021; Uppar et al., 2022; Zhu et al., 2023).
[7]: (Kalam et al., 2017).
[8]: (Afifah et al., 2019; Madusari et al., 2023; Pathmasiri and Perera, 2020).
[9]: (Ahmed et al., 2020; Aravind et al., 2015; Uppar et al., 2022).
[10]: (Obanla et al., 2021; Tulashie and Kotoka, 2020).
[11]: (Ahmad et al., 2022; Heikal et al., 2017; Mobarak et al., 2014).
[12]: (Angulo et al., 2018).
[13]: (Andreo-Martínez et al., 2022).
[14]: (S. Gryglewicz and Gryglewicz, 2003).
[15]: (Hussein et al., 2021).
[16]: (Bañares et al., 2022; Cheah et al., 2020; Hossain et al., 2017; Mohammad Mirzaie et al., 2016; Palomino et al., 2020; Thirugnanasambantham et al., 2020).
*: Oxidation stability of microalgae-based lubricant is 647 h at 20 °C.

lubricants to be used at low temperature.

Thermal stability is the temperature at which lubricants start to decompose. The decomposition temperature of SAE20W40 lubricant – a typical petroleum-based lubricant is 198 °C compared with biolubricant of 257 °C or even higher. It appears that biolubricants have better thermal stability than petroleum-based lubricants.

Being better or comparable to petroleum-based lubricants in many aspects, biolubricants are also inferior to petroleum-based lubricants in a few parameters, including kinematic viscosity, oxidation stability and acid value (Table 1). Viscosity at 40 °C of most biolubricants is <100. The low viscosity of biolubricants may be a drawback in its ability to reduce friction. Chemical or biological modification may result in biolubricants with a better viscosity (Monteiro et al., 2023). Biolubricants also have low oxidative stability (<35.4 h) (Table 1). Thus, biolubricants have a shorter lifetime especially when exposing to air or an oxidizing environment. Chemical additives can be used to improve oxidative stability, but will also add to the cost of biolubricants. Acid value is used to assess the corrosiveness. Biolubricants have higher acid value compared to petroleum-based lubricants. High acid value assists biodegradability but increases corrosiveness, potentially causing damage to engine components or equipment over time.

2.3. Recent evolution of biolubricants

Biolubricants have evolved significantly over the last few decades with several key milestones (Fig. 1). Biolubricants can be readily derived from biodiesel, thus, they can also be classified into three successive generations similar to those of biofuel. Successive releases of these three generations of biolubricants are also largely driven by progress in biofuel development.

The oil crisis of the 1970s due to armed conflicts in the Middle East has spurred early experimentation work for producing 1st generation biolubricants from vegetable oil and animal fat as an alternative feedstock to crude oil (Mann, 2007). Subsequent R&D work for production scale-up and increasing environmental awareness of the detrimental environmental impact of petroleum-based lubricants created several niche markets for biolubricants at the end of the 1990s. These markets include machinery and equipment that deposits oil directly into the environment when it is in operation, food and beverage industry, and applications in highly sensitive environments such as waterways, national parks, wildlife refuges and recreational resorts (Mobarak et al., 2014).

Although environmentally friendly, biolubricant production from crops (such as soybean, rapeseed, olive, and palm) and animal fat can create direct competition for arable land and food security. The diversion of food crops to plant-based oils for biolubricant production may cause an unintended social impact, particularly in areas where food resources are already scarce and food production is limited. In addition, intensive crop cultivation specifically for biolubricant production can disrupt land use patterns leading to increased greenhouse gas emissions, water shortages and pollution. Thus, shortly after the introduction of the 1st generation biolubricants, there has been a rapid transition towards more sustainable and scalable feedstocks.

The 1980s saw the introduction of 2nd generation biolubricants that can be produced from waste materials such as used cooking oil and fat-oil-grease collected from wastewater treatment, agriculture waste, and non-edible oils. While the use of waste materials is consistent with the concept of a circular economy and can eliminate any direct competition with food production, they also have some inherent disadvantages. The consistency of waste materials is low, they have high collection and processing costs, and their availability is also limited and unreliable (Liu et al., 2021; Plata et al., 2022). Non-edible crops like castor, jatropha, and neem can also be used to produce 2nd generation biolubricants. Nevertheless, arable land is still required for cultivating these feedstocks. In addition, the conversion process of non-edible crops into biolubricants is also complex and energy-intensive (Preethi et al., 2021).

Microalgae have recently emerged as a suitable feedstock that can resolve many technical and commercial problems associated with 1st and 2nd generation biolubricants. Commercial microalgae cultivation is possible on non-arable land and even over the ocean surface without direct competition with food production. Microalgae also retain all key characteristics of petroleum derived feedstock including reliability, consistency, and scalability. Microalgae have been shown to have extremely high biomass yield with high and consistent lipid and polysaccharide content for biolubricant production. There is also the potential for industrial-scale microalgal cultivation of any quantity of feedstock to produce biolubricants.

Biolubricants have arguably reached market maturity since the 2010s, thanks to sustained research and development efforts over the last few decades to optimize tribological performance and reduce

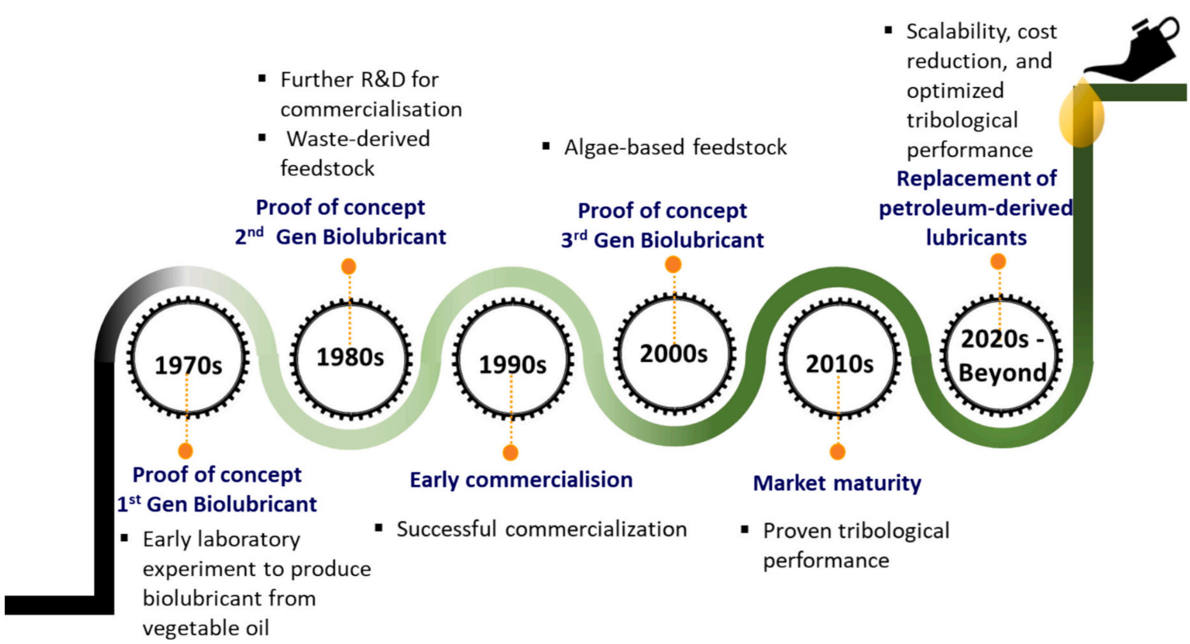

Fig. 1. The evolution of biolubricants from laboratory discovery to current commercial status.

production costs (Hamnas and Unnikrishnan, 2023; Kurre and Yadav, 2023; Mendes et al., 2022). Biolubricants are ubiquitously available from almost all major lubricant suppliers, such as FUCHS, Panolin, ExxonMobil, British Petroleum (BP), and TotalEnergies. However, it is noteworthy that the current market share of biolubricants is still very modest at only about 2 % of the overall lubricant market (Kurre and Yadav, 2023). Indeed, biolubricants are still constrained to mostly niche applications, mostly due to high production costs and some tribological performance issues. It is noteworthy that the term "rapidly biodegradable lubricants" is often used for marketing purposes. This is because in addition to materials produced from bio-feedstock, there are a range of additives, some of which may not be of organic origin, in these rapidly biodegradable lubricants. The small market share of biolubricants highlights the need for further development for biolubricants to completely replace petroleum-derived lubricants.

2.4. Microalgae feedstock

Microalgae are an ideal feedstock for biolubricant production in terms of scalability. As microscopic photosynthetic organisms, microalgae can efficiently convert sunlight and CO_2 into lipid rich biomass without competing for arable land and essential resources. Compared to land-based crops, microalgae have a much higher growth rate and lipid yield (Li et al., 2020). In general, microalgae reproduce and double their cells every 24 h (Moazami et al., 2011). Lipid or carbohydrate content (in dry biomass) of some microalgae can be as high as 75 % and is significantly higher than that of land-based crops, such as soybean (15–20 %), sunflower (25–35 %), and jatropha (30–40 %) (Mata et al., 2010; Patel et al., 2022; Singh et al., 2020). Lipid production per hectare from microalgal cultivation is 7–31 times higher than that from other land-based crops (Udayan et al., 2022). These values in the literature suggest the feasibility of scaling up lipid/ carbohydrate production from microalgae to meet the future demand for biolubricants.

It may also be possible to utilize wastewater to cultivate microalgae at scale (Abdelfattah et al., 2023). Nutrients from wastewater and sequester CO_2 from flue gases can be utilized for microalgae biomass production (Cheah et al., 2015). Thus, microalgae-based biolubricants can potentially be carbon neutral.

Biodiversity is a major advantage of microalgae feedstock. There are about 800,000 known microalgae species (Yin et al., 2020). To date, only about 50,000 of them have been studied but they have shown the potential to thrive in many vastly different aquatic environments to produce microalgal biomass with desirable quality and scalability for biolubricant production. Several strains such as *Chlorella* sp., *Scenedesmus* sp., *Dunaliella* sp., *Botryococcus* sp., *Coelastrella* sp., *and Porphyridium* sp. have been extensively studied and shown the potential for lipid and carbohydrate production (Khan et al., 2024; Mehta et al., 2023; Patel et al., 2022; Udayan et al., 2022).

Scientific and commercial attention has been given towards microalgae for biodiesel production since the energy crisis in the 1970s. Microalgae-based biodiesel production was successfully demonstrated in 1978 (Siddiki et al., 2022). This is followed by several decades of work to further optimize biodiesel production and reduce production costs. Thus, the technical and commercial feasibility of microalgae-based biodiesel has already been demonstrated on a practical scale. The additional step to transform biodiesel into biolubricants has already been demonstrated at practical scale. However, it is noteworthy that the economic competitiveness of microalgae-based biolubricants is highly sensitive to crude oil price and is still rather low.

Economic feasibility is essential for biolubricants to replace petroleum-based products. At the time of this review, biolubricants, such as Vasco 7000, an ester-based metal working lubricant, are available at around \$8/kg. Food-grade biolubricants are more expensive at about \$12/kg. However, food-grade biolubricants are in a special market as they are required for equipment such bearing and conveyor bells in food processing. In comparison, petroleum-based lubricants are in the range from \$4.0/kg to \$4.5/kg (Khan et al., 2022; Uppar et al., 2024).

The cost structure of microalgae-based biolubricants is expected to be similar to those of 1st and 2nd generation biolubricants. Biomass production cost is estimated at up to \$2.2/kg biomass (Branco-Vieira et al., 2020). Significantly additional costs are expected from subsequent production steps including lipid and polysaccharide extraction, processing, and formulation. Thus, microalgae-based biolubricants can be competitive with other specialized biolubricants but is not yet competitive to petroleum-based products, until production cost associated with producing microalgal biomass and extracting precursor chemicals can be substantially reduced.

To expand biolubricant applications beyond the current market niche, it is essential to lower the production cost by improving harvesting, lipid/ polysaccharide extraction, microalgae strain selection and cultivation. The current high cost of microalgal biomass harvesting and lipid/polysaccharide extraction is a major hurdle to further expansion of the microalgae-based biolubricant market. There are also challenges associated with scaling up production or optimizing biomass productivity. The yield of lipid and carbohydrate production in microalgae is dependent on strains. Different strains of microalgae can have varying capacities for these biomolecules' accumulation. Thus, it is vital to determine and characterize microalgae strains for their suitability and high lipid and carbohydrate productivity in terms of fatty acid/ polysaccharide profile and tribological properties. It is arguable that oleaginous microalgae strains exhibit excellent physicochemical and tribological properties owing to their high amount of monounsaturated fatty acids (oleic acid C18:1 content) making them the most suitable for biolubricant production (Patel et al., 2021).

3. Microalgae-based biolubricants

Together with the recent surge in microalgae derived biodiesel research, there has also been significant commercial interest in microalgae-based biolubricants. Nevertheless, to date, very few attempts have been made to develop a research roadmap to realize the full potential of microalgae-based biolubricants. Borah et al. (2021) demonstrated the commercial potential of microalgae for producing carbohydrate lubricant. They also delineated the significance of physicochemical properties (e.g. molecular weight, crystallinity, and rheology) of carbohydrate biolubricants with respect to potential applications. In another review, Farfan et al. (2022) highlighted key benefits of microalgae-based biolubricants. They also suggested a framework for selecting microalgae strains for lipid extraction and biolubricant production. Ijaz Malik et al. (2023) reviewed recent advances in biolubricant synthesis. They singled out microalgae as the most potential feedstock for biolubricant synthesis to address challenges related to food security and greenhouse gas emission reduction.

The three recent reviews above are important contributions to further development of microalgae-based biolubricants. However, they remain limited in scope and only cover a subset of the microalgae biolubricant supply cycle (Fig. 2). As illustrated in Fig. 2, a complete circularity of microalgae-based biolubricants consists of four major components, namely (1) microalgae cultivation, harvesting, and biochemical extraction; (2) lipid and carbohydrate processing for biolubricant production; (3) tribological performance; and (4) biodegradation assessment. The microalgae to biolubricant supply cycle in Fig. 2 allows for identifying major knowledge gaps through a systematic analysis of all peer-reviewed literature related to microalgae-based biolubricants. They include processing and scaling up for biolubricant production from both lipid and carbohydrate sources, advancements in enhancing tribological performance, techno-economic analysis, and biodegradation assessment of final microalgae-based biolubricant products.

A notable gap revolves around the first component (microalgae cultivation, harvesting, and biochemical extraction) in Fig. 2 regarding microalgae-derived lipids and polysaccharides that can be further

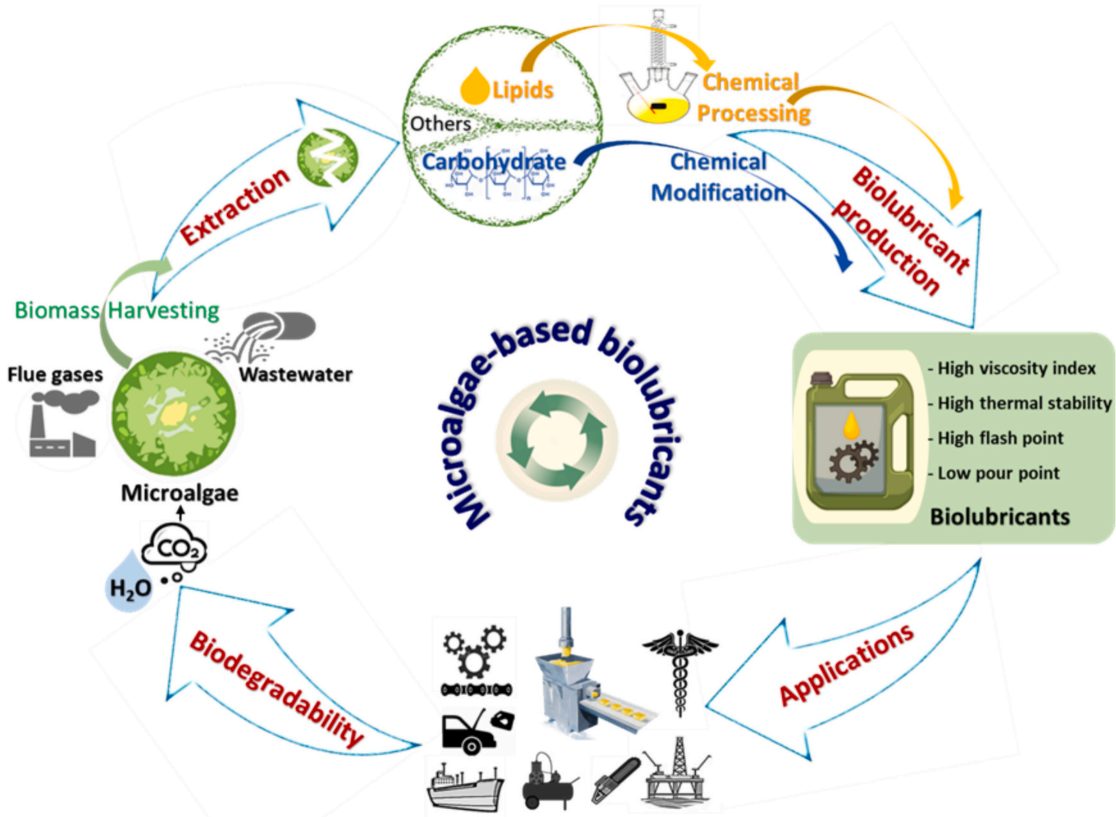

Fig. 2. Overview of the microalgae to biolubricant supply cycle.

Table 2
Previous studies on microalgae-based biolubricants.

Reference	Base biomolecules	Microalgae strains	Observation	Applications	Techno-economic analysis
(Khan et al., 2024)	Lipid	*Coelastrella* sp., *Chlorocystis* sp., *Ceatocerous* sp., *Neochloris* sp., *Picochlorum* sp., *Tisochrysis* sp., *Tetraselmis* sp., *Synechococcus* sp.	Microalgal screening, biolubricant synthesis and characterization from marine microalgal biomass	Automotive and other industrial applications	No
(Kutluk and Kutluk, 2023)	Lipid	*Chlorella protothecoides*	Optimized lipase-catalysed esterification reaction for microalgae-based biolubricant synthesis	–	No
(Khan et al., 2022)	Lipid	*Chlorella sorokiniana*	Chemical modification and additive-based routes for physicochemical property improvement	Automotive, food grade, metalworking, heat transfer	Yes
(Patel et al., 2021)	Lipid	*Auxenochlorella protothecoides* *Chlorella sorokiniana*	Tribological performance assessment	Automotive	No
(Silva et al., 2020)	Lipid	*Dunaliella salina*	Enzymatic catalysis for enhancing transesterification	–	No
(Palomino et al., 2020)	Lipid	*Spirulina* sp. *Chlorella vulgaris*	Hydrothermal liquefaction technology for microalgae-based biocrude production	Biocrude	No
(Thirugnanasambantham et al., 2020)	Lipid	*Chlorella* sp.	Wear and friction characterization	Engine oil	No
(Cheah et al., 2020)	Lipid	*Chlorella* sp.	Physicochemical and tribological property assessment for engine applications Chemical modification to improve tribological properties	Hydrogen-powered engine	No
(Mohammad Mirzaie et al., 2016)	Lipid	*Chlorella vulgaris*	Cheap substrate-based mixotrophic cultivation for lipid production	–	No
(Shoshana et al., 2006)	Carbohydrate	*Porphyridium* sp.	Rheological property assessment	Synovial fluid, contact lenses, catheters, and artificial esophagi	No

processed into biolubricants. Improving tribological performance of microalgae-derived biolubricants is another significant research gap. There is also limited understanding and capability in analyzing technical and economic performance to identify the most efficient and cost-effective technology in the production of microalgae-based biolubricants. In addition, the biodegradation assessment of microalgae-based biolubricants is still poorly understood and further work is necessary to meet regulatory requirements and ensure their environmental compatibility, sustainability, and safety.

Table 2 summarizes specific and recent works to address some of the knowledge gaps identified above. Early research focused on demonstrating the compatibility of microalgae-based biolubricants for commercial applications. Shoshana et al. (2006) indicated that biolubricants made from the sulfated polysaccharide of the red microalgae - *Porphyridium* sp. possess good thermal stability and the ability to reduce friction and wear and can be applied in biomedical applications. Cheah et al. (2020) assessed the physicochemical and tribological properties of microalgae-based biolubricants synthesized from *Chlorella* sp. Their findings indicated that modified microalgae oils possessed great anti-friction and anti-wear potential and could be applied in hydrogen-powered engines. Thirugnanasambantham et al. (2020) examined the wear and friction properties of modified microalgae oils. The authors suggested the potential for these modified microalgae oil to serve as a substitute for the mineral oil 5 W-30 in engine oil applications.

Lipid is the key ingredient for biodiesel production. Thus, technologies for biolubricant production from microalgae lipids can be readily adapted from the biodiesel industry due to shared processes and methodologies. Both biodiesel and biolubricants derived from microalgae involve similar initial steps, such as cultivation, harvesting, and lipid extraction. The techniques employed for lipid extraction in biodiesel production, for instance, are applicable to extracting lipids from microalgae for biolubricant production. Furthermore, the subsequent conversion processes, such as transesterification in biodiesel or modification techniques in biolubricants, also have several common steps. de Sá Parente et al. (2023) conducted a comprehensive techno-economic analysis using biodiesel as a feedstream for biolubricant production. Their study demonstrated that the approach led to a 21 % reduction in capital expenditure and lowered biolubricant prices by over 19 %.

To increase the economic viability of microalgae-based biolubricant industry, recent research efforts have prominently shifted towards techno-economic analyses (Table 2). Advanced conversion technologies and economic feasibility are considered critical aspects of this field. Analyzing these aspects not only aids in determining the economic sustainability of large-scale production but also guides decision-making processes for industry stakeholders and policymakers towards biolubricants derived from microalgae. Khan et al. (2022) reported that biolubricant produced by the additive route are more cost-effective compared to those produced through the chemical route. The author also highlighted that the techno-economic feasibility of microalgae-based biolubricants could be improved by implementing biorefinery approach. These findings provide a foundation for further research on advances in production methods for cost-effective biolubricants.

The tribological performance improvement is also essential for the widespread adoption of microalgae-based biolubricants. Enhancing tribological performance, including friction reduction, wear resistance, and effective lubrication, enables the versatile utilization of biolubricants across diverse industries. Each industry demands specific biolubricant properties to suit its unique operational requirements. The tailored characteristics of biolubricants contribute to optimal performance within varied sectors.

The biolubricant market is projected to grow steadily and interest within the broader biolubricant industry. Rising oil prices, coupled with concerns regarding oil supply security, pay the way for further expansion of the biolubricant market. As industries increasingly prioritize eco-friendly and renewable alternatives, the demand for microalgae-based biolubricants is rising across various sectors. Microalgae-based biolubricants find application across various industries due to their environmentally friendly nature and functional properties (Table 2). Some common applications of biolubricants include automotive, industrial machinery, and marine industries. Biolubricants are also used in specialized areas such as food-grade lubricants for the food processing industry, beverage manufacturing, pharmaceuticals, and cosmetics, where safety, biodegradability, and non-toxic properties are crucial.

4. Research priorities

Despite significant progress in industrial-scale biofuel production from microalgae, further research is still necessary to enhance the production, sustainability, application, and cost-effectiveness of microalgae-based biolubricants. Key research priories in the coming years include (1) selection of suitable microalgae strains; (2) large-scale and low-cost microalgae cultivation; (3) efficient lipid/polysaccharide extraction and processing; and (4) tribological performance evaluation and optimization (Fig. 3). These research priorities are essential for the development of the microalgae-based biolubricant industry. In addition, the integration of digital technology holds great potential to significantly improve the economic efficiency and precision of processes (Fig. 3).

4.1. Microalgae strain selection

The commercialization of microalgae-based biolubricant scale has spurred the need for large scale, consistent, and low-cost microalgae production and processing. Successful transition from proof-of-concept knowledge in the laboratory to large-scale production requires systematic strain selection and cost-effective reactor design.

With about 1 million microalgae species, strain selection is essential for meeting the scale demand of commercial production. 'Elite' microalgae strains can be defined in terms of their fast growth rate, resilience to environmental disturbance and competition (with other microalgae strains or bacteria), and lipid or polysaccharide composition and content for subsequent biolubricant production.

Several microalgae strains have shown significant potential for biolubricant production, in terms of their high lipid and polysaccharide content as well as their fatty acid methyl ester (FAME) and carbohydrate profiles for subsequent biolubricant production. High yield of palmitic, linoleic, and oleic acid have been reported from specific strains of *Chlorella* sp., *Scenedesmus* sp., and *Coelastrella* sp. (Jahromi et al., 2022; Kona et al., 2022; Susanti et al., 2024). Microalgae derived FAME can offer both high oxidative stability and consistent cold flow properties (Nayana et al., 2022). *Chlorella* sp. and *Scenedesmus* sp. also have high polysaccharide yield (Grubišić et al., 2024). *Porphyridium* sp. can produce unique profile of sulfated polysaccharides and thick extracellular polymeric substances, for enhancing biolubricant tribological properties (Netanel et al., 2016).

There has been significant technological progress in phenotyping, gene selection, and digitalization to realize the full potential of strain selection (Fabris et al., 2020). For example, high throughput phenomics can be used to rapidly screen algal strains, mutants, and transformants in a dynamic environment (Argyle et al., 2021).

High throughput phenomics can be employed to evaluate various traits such as growth rates, stress tolerance, and lipid or carbohydrate production. Automated systems equipped with imaging technologies, such as high-resolution cameras and sensors, capture real-time data on microalgal cultures under controlled conditions. The data is then processed to generate detailed phenotypic profiles for each strain (Argyle et al., 2021).

Techniques to induce mutations to select microalgae strains of desirable characteristics have also been demonstrated (Trovao et al., 2022). Chemical mutagenesis, using agents such as ethyl methanesulfonate, can create random mutations by altering DNA sequences. This technique has been shown to enhance traits in microalgae, including

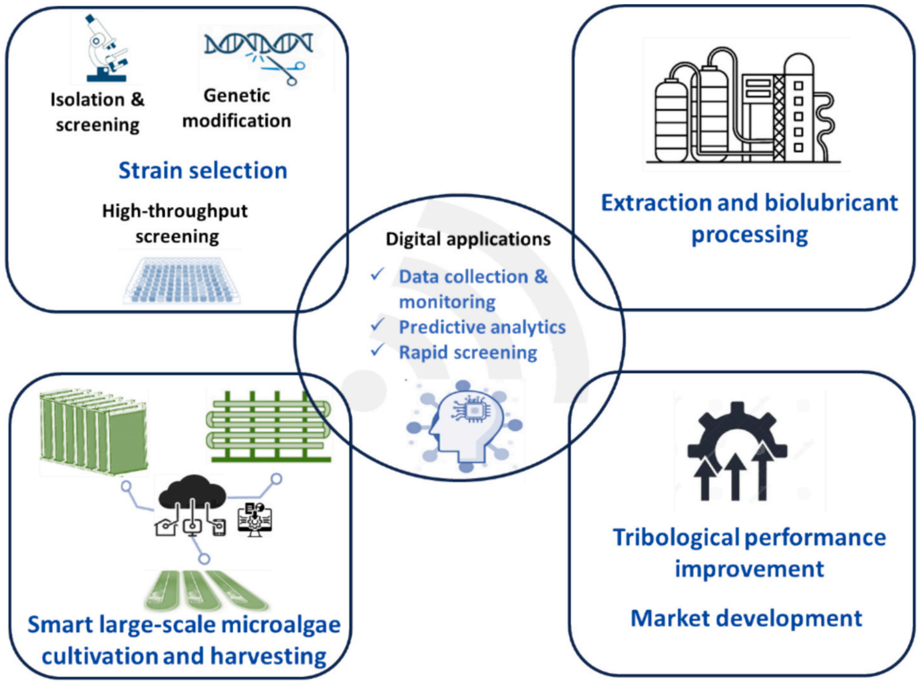

Fig. 3. Overview of critical research priorities for the production of microalgae-based biolubricants.

lipid production (Dinesh et al., 2018). Physical mutagenesis, through exposure to laser irradiation, induces DNA damage, leading to mutations. This method can improve microalgae biomass production and lipid accumulation (Xing et al., 2021).

Genetically engineered strains can also be obtained from techniques, such as CRISPR/Cas9 gene editing. In these techniques, genes are cut at specific DNA sequences for introducing changes within the genome (Dhokane et al., 2023; Patel et al., 2023). CRISPR technology has the potential to significantly microalgal biomass production efficiency and lipid/polysaccharide yield (Trovao et al., 2022).

Machine learning has also been used for bioprospecting and screening microalgae strains for the production of bioactive compounds (Chong et al., 2023). By analyzing vast amounts of data from various sources, including genetic sequences, metabolic profiles, and environmental conditions, machine learning algorithms can identify patterns and predict the potential of different microalgae strains. These algorithms help researchers uncover hidden relationships between genetic traits and desired production outcomes, such as high yields of biomolecules. Additionally, machine learning facilitates the automation of screening processes, enabling the rapid evaluation of large numbers of strains under diverse conditions.

Strain selection is still an emerging research area, focusing on the broad issue of industrial-scale microalgae biomass production. Nevertheless, studies specific to microalgae-based biolubricant production are expected in the near future given significant scientific and commercial interest.

4.2. Large-scale and low-cost microalgae cultivation

Recent research efforts for developing large-scale and cost-effective biomass production focus primarily on optimizing growth conditions and refining cultivation techniques (Jui et al., 2024; Regina et al., 2024). While inorganic carbon and nutrients serve as essential substrates for microalgae growth, biomass productivity is also greatly influenced by other environmental factors such as light, temperature, pH, and mixing (Okoro et al., 2019). Cultivation systems are designed to regulate these environmental conditions.

Previous research has highlighted the importance of optimizing the balance among key inputs including inorganic carbon, light (energy), and nutrients for high rate microalgae production. Carbon input is essential to cell growth. CO_2 input affect the growth rate, microalgae cell content (e.g. lipid yield) and even the FAME profiles. Changes in the proportion of saturated, monounsaturated, and polyunsaturated fatty acids are reflected in the FAME profiles, influencing the quality and properties of biolubricants. Carbon supply to the photobioreactor is achievable by either direct CO_2 inject or biocarbonate addition. Eloka and Inambao (2017) demonstrated that the addition of 1 % (v/v) CO_2 enhanced microalgal growth, resulting in a 60 % increase in the average growth rate. Wu et al. (2019) reported that cultivating using 0.15 % (v/v) CO_2 is beneficial to both lipid accumulation and growth rate. Carbon can also be added as bicarbonate (e.g. $NaHCO_3$ or $KHCO_3$), particularly in systems where the addition of gaseous CO_2 is impractical (Yang et al., 2024). Bicarbonate addition has shown accelerated biomass production rate and high lipid/polysaccharide yield (M. Chen et al., 2021; Z. Chen et al., 2021). Srinivasan et al. (2018) reported that cultivating microalgae with the addition of sodium bicarbonate (100 mM) under nutrient deficiency conditions significantly increased biomass production and lipid content.

Nutrient availability is also a vital factor that fundamentally determines the maximum achievable biomass productivity (Qian et al., 2024). Concentrations and ratios of essential nutrients, such as nitrogen and phosphorus, impact on microalgae growth and compound accumulation (Policastro et al., 2024). Nitrogen and phosphorus are particularly important for cellular division and the synthesis of proteins, lipids, and carbohydrates (Yaakob et al., 2021). However, when nutrient availability is limited, microalgae shift their metabolism towards compound accumulation as a survival mechanism. This principle is applied as an effective strategy to promote lipid/polysaccharide contents. Nagappan and Kumar (2021) demonstrated that nitrogen deficiency could increase lipid and polysaccharide content by up to 2 and 1.5 times, respectively. Similar to nitrogen, a limited phosphorus concentration in the culture could support cell growth as well as enhance lipid accumulation. Trace elements such as iron, magnesium, copper, molybdenum, and zinc act as cofactors in enzymatic reactions that drive various metabolic pathways, including those involved in lipid production (Dou et al., 2013). By carefully managing the levels of these nutrients, it is possible to optimize both the growth of microalgae and the yield of lipids and polysaccharides.

Light (energy input), temperature, and mixing are other important factors for microalgae growth and compound synthesis (Chowdury et al., 2020). Sufficient light exposure is essential for photosynthesis, as light intensity and duration directly impact the photosynthetic efficiency and biocompound production. Esteves et al. (2024) reported that light intensity (1107 μmol m^{-2} s^{-1}) significantly enhanced the accumulation of carbohydrates to 30 % and lipids to 13 %. Microalgae thrive within specific temperature. Most microalgae grow well in the temperature range of 20 °C to 30 °C, though specific species may have slightly different requirements (Ali et al., 2024; Barten et al., 2020). Mixing also contributes to an optimal environment. Mixing prevents cell settling and promotes uniform light exposure, nutrient availability, gas exchange, and temperature regulation, contributing to higher productivity. Mixing can be done through aeration, stirring, or a combination of both (Uyar et al., 2024). To ensure these environmental parameters are well controlled, specialized cultivation techniques have been developed.

In recent years, new and innovative microalgae cultivation configurations have been commercialized and introduced to the market. These new configurations often aim to scale up microalgal biomass production and product consistency to meet the quantity and quality requirements for commercial biolubricants (Regina et al., 2024). Table 3 summarizes the key advantages and disadvantages of conventional open pond configurations in comparison to newer and more sophisticated enclosed photobioreactors (Table 3).

Traditional microalgae cultivation techniques rely mostly on open structures such as raceway ponds to minimize capital and operational costs. Open ponds can be easily replicated to increase production capacity; however, they have a very high demand for land space. Open pond microalgae cultivation also has low maintenance requirements and simple operations (Kaloudas et al., 2021). Thus, without considering the cost of land or open space, the unit cost of biomass production by open ponds is often lower than enclosed photobioreactors.

While open ponds offer flexibility for scaling up, achieving stability and maintaining biomass quality can be challenging. Open ponds have low biomass productivity. Microalgal biomass production by a raceway pond is up to 12 times lower than an enclosed photobioreactor (Novoveska et al., 2023). High risks of contamination and less controlled environments cause negative effects on the purity and consistency of biomass (Laezza et al., 2022). Open ponds are typically larger and need to be spread out over a considerable area to prevent shading and allow each microalgae cell to maximize sunlight exposure. Contaminants are thus more likely to enter the pond, including unwanted microalgae strains, bacteria, or other organisms that can adversely affect microalgae cultivation. Land demand and significant water loss through evaporation are also issues associated with open ponds (Table 3).

Table 3
Comparison between open ponds and enclosed photobioreactors.

	Open pond	Enclosed photobioreactor	References
Configuration	Raceway Aerated pond	Flat panel Tubular Column Polyethylene bags	(Kaloudas et al., 2021; Sirohi et al., 2022)
Scalability	Easy	unknown	(Jeevanandam et al., 2020)
Biomass production (g/L·d)	<0.12	<1.5	(Chisti, 2007)
Lipid production cost ($/L)	3.36	8.35	(Richardson et al., 2012)
Biomass quality	Variable	Stable	(Bošnjaković and Sinaga, 2020)
Physical parameter control	Poor	Good	(M. Chen et al., 2021; Z. Chen et al., 2021)
Evaporation (L_{water}/Kg of lipid)	530	Insignificant	(Poddar et al., 2022)
Maintenance	Easy	Difficult	(Richardson et al., 2014)
Contamination risk	High	Low	(Novoveska et al., 2023)
Land requirement	Large	Small	(Novoveska et al., 2023)
Biofilm formation/fouling	Low	High	(Huang et al., 2017)
Harvest efficiency	Low	High	(Grubišić et al., 2019)

Enclosed photobioreactors have recently emerged as a major breakthrough in large-scale microalgal biomass production. A variety of enclosed photobioreactor configurations including flat panel, tubular, column, and polyethylene bags have been introduced to the market (Benner et al., 2022; Penloglou et al., 2024). Closed photobioreactors offer high biomass productivity and qualitative lipid and carbohydrate sources. These advancements in microalgae cultivation provide better control over environmental conditions, such as light through improved light paths for consistent illumination, temperature, pH, and minimized contamination risk (Wang et al., 2012). Enclosed photobioreactors are well-suited for research and high-value product production when precise control is essential (Manu et al., 2024).

Scaling up the production of microalgae using enclosed photobioreactors is more challenging than open structures. The high initial investment for the construction of enclosed photobioreactors can be a significant barrier to scaling up (Bošnjaković and Sinaga, 2020). It was estimated that the CAPEX cost for photobioreactors is over 2.5 times higher than that for open ponds (Richardson et al., 2012). In addition, the maintenance work of photobioreactors is complex and demands a higher level of technical expertise and operational oversight. Regular cleaning is required to remove biofouling from photobioreactor walls, ensuring optimal lighting conditions for microalgae growth. Maintenance costs account for up to 40 % of the OPEX expenses (Davis et al., 2011).

Despite the relatively high construction and operational costs, commercial demand has driven mass microalgae production towards the application of enclosed photobioreactors to enhance yields and quality of biomass (Sarker and Kaparaju, 2023). Advances in technology accelerate the operational costs to be minimized for the application of enclosed photobioreactors to be more practical for industrial-scale biomass production (Abdur Razzak et al., 2023).

Recent advancements in photobioreactor designs have resulted in cost reduction and improved sustainability. Innovations such as enhanced light distribution systems, improved gas exchange mechanisms, and the integration of automation and real-time monitoring technologies have increased the efficiency of photobioreactors (Borowiak et al., 2021; Kishi et al., 2021; Nwoba et al., 2019). These improvements lead to higher biomass yields with lower energy consumption, directly reducing the costs of cultivation. The development of closed-loop systems within photobioreactors has furthered sustainability efforts (Samoraj et al., 2024). In closed-loop systems, water, nutrients, and CO_2 are continuously circulated and reused within the cultivation environment (Bele et al., 2023). The application of closed-loop systems reduces the need for fresh inputs, lowers operating costs, and minimizes environmental impact.

There have been a surge of start-ups and new joint ventures to develop and commercialize new photobioreactors for large-scale microalgae production. Examples include Algaecytes, AlgaeLab Systems, Algae Production Systems (APS), and Algaetech International. They offer new photobioreactor technologies for research and large-scale microalgae production for biofuel, pharmaceuticals, and nutraceuticals. Additionally, industry leaders like Varicon Aqua Solutions, Heliae Development, and Solix BioSystems also contribute to the market with techniques to enhance the efficiency and scalability of enclosed photobioreactors. The increased competition and higher demand are expected to lead to cost reductions.

Enclosed photobioreactor configuration allows for the integration of IoT and AI technologies to enhance biomass productivity and quality.

IoT hardware and machine learning are applied resulting in accurate prediction and well-controlled microalgae growth (Lim et al., 2022). The IoT and machine learning solutions are adaptable to different scales of cultivation, from small-scale research setups to large commercial production facilities. Equipped with sensors, IoT devices monitor and make adjustments, contributing to optimizing resource usage, minimizing waste, and maximizing the efficiency of nutrient and energy consumption (Wang et al., 2022). Large-scale microalgae cultivation with low costs is a prerequisite for successful microalgae-based biolubricant production. As the world transitions into a digitalized industry, further development involving the integration of AI and IoT into mass microalgae production or smart cultivation is necessary for economic feasibility.

4.3. Microalgae harvesting

Biomass harvesting is another major bottleneck in scaling up microalgae-based biolubricant production. Using current techniques, microalgae harvesting accounts for up to 30 % of the total cost of biofuel production (Ananthi et al., 2021; Tan et al., 2020). This is because microalgae cells are small (2–20 μm in diameter), negatively charged, and only occur at diluted concentrations in the mature cultivation solution (0.5–5 Kg/m^3) (Chan et al., 2023; Zhang et al., 2022). Flocculation in combination with either centrifugation, flotation, filtration, or sedimentation has been used at industrial scale for microalgae harvesting with biomass recovery efficiencies of over 90 % (Liu et al., 2023; F. Liu et al., 2023; Rao et al., 2024). Cost advantages, efficiency, and energy consumption of these practical techniques are shown in Fig. 4.

Flocculation is a practical and low-cost method for harvesting microalgae (Mehta and Chakraborty, 2021). Flocculation allows for individual microalgae cells to attach together to form large aggregates for subsequent removal from water by another step such as centrifugation, sedimentation, filtration, or flotation. It is noteworthy that without flocculation, these additional steps (centrifugation, flotation, filtration, or sedimentation) cannot efficiently recover and separate microalgae from water.

Flocculation followed by centrifugation for biomass harvesting yields a complete 100 % recovery efficiency. However, centrifugation is energy-intensive, requiring up to 9 kWh to process one m^3 of microalgae solution, significantly escalating the harvesting cost to as high as 1.8 $/Kg biomass (Fig. 4). Additionally, centrifugation involves spinning a mixture at high speeds to separate components, contributing to the complexity of the system.

Flocculation combined with flotation can achieve about 92 % recovery efficiency (Fig. 4). The flotation process consumes more energy compared to sedimentation and filtration due to the introduction of microbubbles into the culture medium. Energy demand for flotation was estimated 3.8–7.6 kWh/m^3, leading to the cost of harvesting up to 0.4 $/Kg of biomass. Similar to centrifugation, flotation requires a complex system. For successful flotation, specialized equipment such as spargers or dissolved air flotation (DAF) systems are used to collect microalgal cells (Xia et al., 2017).

The combination of flocculation and filtration reduces blockage and can achieve a recovery efficiency of over 99 %. The estimated cost of microalgae harvesting by flocculation-filtration method is up to about 0.27 $/Kg biomass (Fig. 4). Harvesting by flocculation-filtration can be implemented by using mesh sieves or textile membranes capable of filtering flocs of microalgae cells (Ahn et al., 2020; Kumar et al., 2019). This approach is simple and low-cost. A dynamic filtration process can also be used and be more effective. However, dynamic filtration systems are more complex and require high energy and equipment costs (Castro and Garcia, 2021).

Sedimentation without flocculation can only recover 10 % of the microalgae biomass. By contrast, a combination of flocculation and sedimentation can achieve over 98 % biomass recovery. The cost of microalgae harvesting through flocculation-based sedimentation is merely 0.23 $/kg of biomass, requiring only 0.1–0.2 kWh of electricity per m^3 of microalgae processed (Fig. 4). The flocculation-sedimentation method is also simple and can be applied effectively across various scales (Badawi et al., 2023). The finding indicates that flocculation followed by sedimentation stands out as the most scabble and economically-efficient harvesting method among the harvesting techniques.

In flocculation-based sedimentation/ filtration, flocculant is introduced to aggregate small microalgal cells into larger flocs that can be separated by gravity through sedimentation. Several typical flocculants used in the flocculation process have been extensively studied, including inorganic metal salts (e.g. aluminum sulfate and ferric chloride) (Morais et al., 2023; Vu et al., 2020) and polymers (e.g. polyacrylamide (PAM) and chitosan) (Aditya et al., 2024; Nguyen et al., 2022; Shaikh et al., 2021).

Polymer flocculants have been proven to be effective, economical, environmentally friendly, and scalable for microalgae recovery. A very high polymer dosage is required to achieve a recovery efficiency of 99 %

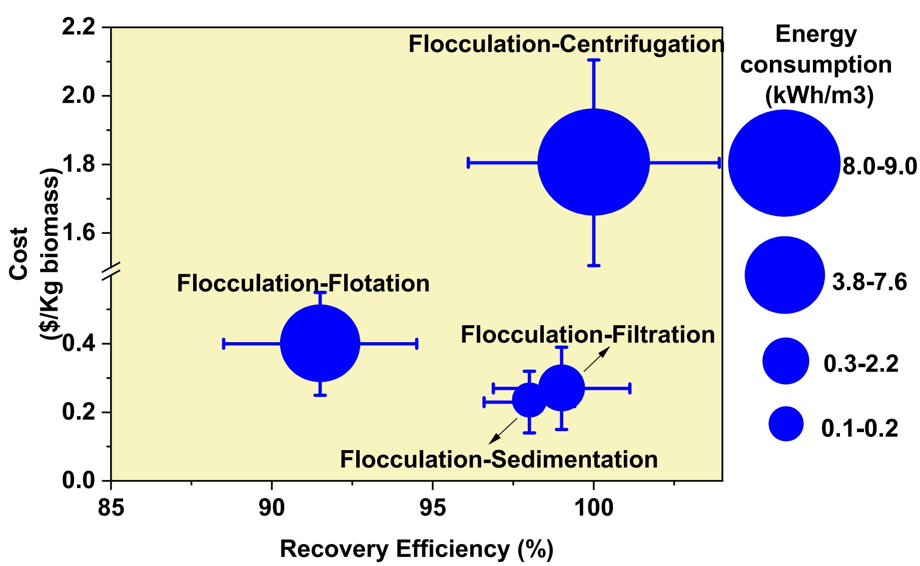

Fig. 4. Biomass recovery efficiency and cost under different harvesting methods (Gerardo et al., 2014; Goswami et al., 2019; Leite and Daniel, 2020; Leite et al., 2020; Najjar and Abu-Shamleh, 2020; Vu et al., 2021; Xia et al., 2017; Xu et al., 2021; Zhang et al., 2023; Zhao et al., 2020; Zhu et al., 2018).

(Yang et al., 2021). Utilizing cationic polyacrylamide polymer instead of ferric chloride for flocculation could potentially reduce the cost of flocculants per ton of dry biomass by threefold (Vu et al., 2020). The combination of natural and chemical flocculants can enhance recovery efficiency while simultaneously lowering costs (Ogbonna and Nwoba, 2021; Vu et al., 2020).

Innovative flocculants do not only offer improved efficiency in harvesting microalgae but also minimize environmental impact and reduce production costs. Further exploration of natural flocculants is expected to extend harvesting more economically. The flocculant for microalgal harvesting should be determined through careful experimentation and optimization based on factors such as microalgal species, cell density, pH, and the presence of other contaminants (Matter et al., 2019; Ummalyma et al., 2016). Tech-economic analyses and environmental sustainability should also be considered in the selection process to ensure the overall efficiency and viability of the bulk harvesting.

4.4. Extraction and biolubricant processing

Biomolecules suitable for lubricant production are located in different parts of the cells. Lipids are stored within lipid bodies inside microalgae cells while polysaccharides can be found in both the cell wall and internal structure (Babich et al., 2022). The two main types of polysaccharides in microalgae cells are soluble exopolysaccharides (S-EPSs) released into the culture medium and bound polysaccharides (B-EPSs) accumulating inside of cells. This distinction is important when designing extraction methods for lipids and polysaccharides.

Lipid and polysaccharide extraction accounts for one-third or more of the cost of microalgae-based biolubricant production (Vasistha et al., 2021). In addition to lipids and polysaccharides, there are also other components in microalgae biomass such as proteins, pigments, and cell debris that must be separated for utilization in other applications (Obeid et al., 2022). Extraction processes help isolate lipids and polysaccharides, ensuring the purity and quality of the extracted compounds. This purification step is crucial for producing high-quality biolubricants with consistent performance and characteristics. Together with the requirement for high extraction yield, it is also necessary to consider chemical usage and energy consumption for achieving an economically viable, environmentally friendly, and scalable process (Abdel Ghaly, 2015).

A range of biomolecule extraction methods for biolubricant conversion has been explored, reflecting significant advancements in extraction technology. Each method offers unique advantages in terms of extraction efficiency, energy consumption, scalability, and environmental friendliness (Table 4). Some are relatively simple but are used mostly on a small scale for laboratory studies. There are also several emerging extraction methods with the potential for scaling up and cost reduction but have yet to be commercialized.

Conventional methods (i.e. Bligh and Dyer, Folch, and Soxhlet) for lipid extraction often involve the use of a toxic solvent (Ren et al., 2017; Zhou et al., 2022). These solvents are used to dissolve and extract lipids from microalgae cells. This practice consumes a large amount of volatile organic solvents (e.g. ethanol, methanol, chloroform, and n-hexane) while low lipid recovery is obtained (Bitwell et al., 2023). A low lipid extraction efficiency (<30 %) was observed (Table 4). Bligh and Dyer, and Folch methods are widely used in laboratories for their efficiency in

Table 4
Biomolecule extraction methods for biolubricant production.

		Extraction techniques	Extraction efficiency (%)	Energy consumption (MJ kg^{-1} dry biomass)	Scalability	Environmental friendliness	References
Lipid extraction methods	Conventional	Bligh and Dyer Folch Soxhlet	28 25 20	4–9	**	*	(Ahn et al., 2020; Cavonius et al., 2014; He et al., 2019; Ren et al., 2017; Tan et al., 2020; Zhou et al., 2022)
	Emerging	Ultrasound-assisted	82	147	**	**	(Ferreira et al., 2016; Jaeschke et al., 2017; Ren et al., 2017)
		Microwave-assisted	88–100	2.5–65	**	**	(Iqbal and Theegala, 2013; Kapoore et al., 2018; Zhou et al., 2019)
		Ionic liquids	99	0.4	**	**	(Egesa and Plucinski, 2022; Motlagh et al., 2021)
		Supercritical fluid	92–100	40	***	***	(Lorenzen et al., 2017; Tzima et al., 2023; Yen et al., 2015)
		Subcritical water	75	16	***	***	(Ho et al., 2018; Huang et al., 2019)
		Pressurized liquids	42	–	***	**	(He et al., 2019)
		Enzyme-assisted	92	–	*	***	(Wang et al., 2015)
Polysaccharide extraction methods	Conventional	Hot Water	71	–	**	***	(Liu et al., 2023; F. Liu et al., 2023)
		Alcohol precipitation	–	–	**	**	
		Acid Hydrolysis	25	–	**	*	(Chi et al., 2018)
		Alkaline	59	–	**	*	(Liu et al., 2023; F. Liu et al., 2023)
	Emerging	Ultrasonication-assisted	50	–	**	**	(Costa et al., 2021)
		Microwave-assisted	–	–	**	**	(Wassie et al., 2021; Zhang et al., 2024)
		Enzyme-assisted	24	–	*	***	(Patel et al., 2022)
		Subcritical water	66	–	***	***	(Huo et al., 2022)
		Supercritical fluid	–	–	***	***	(Tzima et al., 2023)
		Tangential microfiltration	–	–	***	***	(Li et al., 2011)

Scalability
**: Low scalability*
***: Moderate scalability*
****: Good potential for scalability*
Environmental friendliness
**: Low environmentally friendliness*
***: Moderate environmentally friendliness*
****: High environmentally friendliness*

extracting lipids from small-scale samples. However, the use of large volumes of chloroform makes these methods environmentally unfriendly and needs to be considered for industrial applications. Soxhlet extraction, on the other hand, is more appropriate for industrial-scale biolubricant production. Soxhlet extraction is scalable, capable of handling large volumes of biomass, and allows for the recycling and reuse of solvents, thereby reducing environmental impacts and costs. Solvent-based methods are generally costly and harmful to the environment. It is noteworthy that relying solely on a single extraction process may not be sufficient to achieve the highest yield.

A combination of methods can be utilized to enhance lipid extraction yields (Kiyani et al., 2023; Liu et al., 2023; F. Liu et al., 2023). Mechanical-assisted extraction is an emerging method to enhance lipid extraction while minimizing the use of solvents (Marques et al., 2024; Zhou et al., 2019). Ultrasound-assisted extraction with 40–80 % of ultrasound intensity and 60–75 % of ethanol concentration resulted in an extraction efficiency of 80 % (Jaeschke et al., 2017). Microwave-assisted extraction could achieve a higher lipid extraction efficiency of 88 % in comparison to conventional approaches (Zhou et al., 2022). Zhang et al. (2022) also demonstrated that pulsed microwave-assisted extraction could achieve up to 90 % lipid recovery. In another study, complete lipid recovery was obtained using the subcritical water with microwave extraction (Reddy et al., 2014).

More and more innovative research has been carried out on using green solvents for large-scale lipid extraction (Jeevan et al., 2017; Wang et al., 2024). Ionic liquids, supercritical fluid, and subcritical water show a high lipid extraction efficiency (up to 100 %) while being environmentally friendly methods (Table 4). Ionic liquids using molten organic salts are considered to be more environmentally friendly than conventional volatile organic solvents. Matchim and Lai (2023) reported a novel CO_2-based alkyl carbamate ionic liquid as an efficient solvent for lipid extraction. These authors demonstrated that CO_2-based alkyl carbamate ionic liquid effectively permeabilizes the cell wall of microalgae, resulting in improved lipid extraction. However, the high production cost of ionic liquids restricts their practical application to large-scale operations (Motlagh et al., 2021). Supercritical fluid and subcritical water extraction are typical examples of using green solvents (CO_2 and H_2O, respectively) for extraction. These two practical methods are suitable for continuous processing and can be scaled up for industrial-scale operations. Supercritical fluid extraction has been commercialized for various applications, including the extraction of essential oils, flavors, and nutraceuticals where high-value products justify the higher costs associated with the method (Uwineza and Waskiewicz, 2020). Some companies are exploring supercritical fluid extraction for microalgal biomass on a smaller scale for niche markets, but it is not yet a widespread industrial standard for large-scale lipid extraction. Subcritical water extraction is still largely in the research and pilot-scale phase and has not yet been commercialized for lipid extraction from microalgae. Enzyme-assisted extraction is also a green extraction due to being solvent-free. Enzyme-assisted technique can reduce solvent usage and energy consumption, but the price of enzyme is high and optimization of enzyme concentrations and reaction conditions is required (Qiu et al., 2019; Zhou et al., 2022). These emerging methods continue to be areas of active research and development with the potential for future industrial adoption.

Polysaccharides are polar macromolecules and tend to be more soluble in polar solvents such as water and alcohol. Therefore, extracting polysaccharides from microalgal biomass often involves the use of polar solvents to dissolve and extract effectively (Liu et al., 2023; F. Liu et al., 2023). Conventional methods including hydro-thermal and alcohol precipitation are commonly used based on their compatibility (Liu et al., 2023; F. Liu et al., 2023). Hydro-thermal method (i.e. hot water) is particularly common due to its high polarity, cost-effectiveness, and environmental friendliness. Alcohol precipitation methods using ethanol or methanol are also used for polysaccharide extraction, especially when higher solubility or specific properties are desired. In addition, acid and alkaline methods, as another traditional extraction method, are simple and effectively dissolve polysaccharides (Liu et al., 2023; F. Liu et al., 2023). However, traditional extraction techniques often involve harsh chemical treatments, which can be energy-intensive, time-consuming, and environmentally damaging (Wang et al., 2010).

Emerging methods for polysaccharide extraction from microalgae are revolutionizing. To improve the extraction yield of polysaccharides, two or more extraction methods can be combined. The mechanical-assisted method, for example, utilizes ultrasound waves or microwaves to disrupt cell structures and enhance the extraction efficiency of polysaccharides (Costa et al., 2021; Zhang et al., 2024). Another promising method is enzyme-assisted extraction using enzymes to break down the cell walls of microalgae and release polysaccharides. The enzyme-assisted method results in higher yields and reduced energy consumption (Malvis et al., 2023). Supercritical CO_2 extraction methods using environmentally friendly solvents are also being explored as alternatives to conventional chemical solvents (Tzima et al., 2023). Tangential-flow ultrafiltration can be used to extract soluble EPS from the medium. This technique was conducted to successfully isolate soluble EPS from *Chaetoceros muelleri* and *Spirulina platensis* (Li et al., 2011). These emerging methods offer promising solutions for polysaccharide extraction from microalgae, paving the way for more sustainable and environmentally friendly extraction processes. However, up to date, research on large-scale polysaccharide extraction for industrial-scale biolubricant production has received limited attention. Systemic research on optimization of extraction and energy consumption analysis is expected to be carried out.

After extraction, lipids and polysaccharides can be further processed into biolubricants via several different pathways (Fig. 5). Biolubricants derived from microalgae can be synthesized directly by formulating purified polysaccharides with additives such as antioxidants, modifiers, or defoamers. In contrast, the synthesis of biolubricants from lipids can follow two routes: (1) using additives or (2) chemical modification processes such as transesterification, epoxidation, or estolide formation. These reactions alter the chemical structure of lipids or polysaccharides to improve their lubricating properties and stability (Khan et al., 2022; Khan et al., 2024; Kurre and Yadav, 2023).

Advanced conversion techniques are essential to obtaining high-quality biolubricants. Catalysts, including homogeneous (acids/bases), heterogeneous (metals), and biocatalysts (enzymes) are commonly used to enhance the conversion and selectivity of ester-based biolubricants (Hossain et al., 2018; Monteiro et al., 2023). The optimization of fatty acid methyl esters synthesis using alkali and acid catalysis contributes to high conversion yields of 84 % and 91 %, respectively (Tacias-Pascacio et al., 2019). Lipases have emerged as environmentally friendly and have shown a superior conversion rate (Mendes et al., 2022). Kutluk and Kutluk (2023) optimized esterification reaction by lipase catalysis from *Chlorella protothecoides* and achieved a high conversion rate of oil-free fatty acids up to 93 %. In another study, biocatalyst was used to convert microalgal oil fatty acids into alkyl esters, obtaining an 89 % conversion within 120 h (Silva et al., 2020). Future research should focus on catalytic conversion that would further enhance the performance of biolubricants. The optimization of conversion leads to enhanced sustainability, improved performance, and reduced environmental impacts.

The tribological properties of microalgal-based biolubricants after conversion can be improved by the addition of nanoparticles and additives. The addition of nanoparticles of different metallic compounds could contribute to enhancing anti-wear properties and viscosity of biolubricants (Kutluk and Kutluk, 2023). A reduction of up to 50 % in coefficient of friction was observed when using mixed metal oxide nanoparticles such as $CuZnFe_2O_4$ (Yilmaz, 2019). Additives are also mixed into finished microalgal-based biolubricants to improve or suppress their undesirable properties. Antioxidants, corrosion inhibitors, viscosity improvers, alkalinity improvers, and anti-foam agents are commonly used (Kurre and Yadav, 2023). These agents are responsible

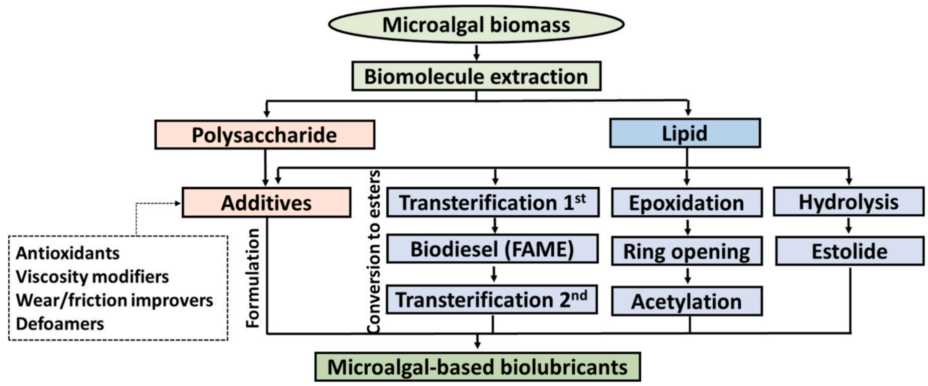

Fig. 5. Flow diagram for biolubricant production from microalgae.

for improving several poor tribological properties of microalgae-based biolubricants such as low viscosity index, low oxidative stability, and high acid value (as previously summarised in Table 1). Future research should be focused on such additives and nanoparticles that would facilitate the synthesis of microalgal-based biolubricants with superior lubrication properties.

4.5. Market development

Biolubricants are already widely used in important sectors such as food processing and pharmaceutical industries (Ramchuran et al., 2023). In the food and beverage industry, food-grade biolubricants are required if they may come into contact with food products. Food grade lubricants are essentially biolubricants that have been formulated to be non-toxic and odorless. In health care, biolubricants also play a critical role in the development and maintenance of medical devices and equipment. Biocompatible lubricants are used in surgical instruments, diagnostic tools, and prosthetics to reduce friction, prevent wear, and ensure smooth operation. These applications not only improve the functionality and reliability of medical devices but also enhance patient outcomes by reducing the risk of infection. Another specific application involves injectable biolubricants, which researchers in Australia are developing for osteoarthritis patients (AIBN, 2024). These biolubricants are being explored as a treatment option to alleviate pain and improve joint function by mimicking the natural lubrication of healthy joints. These efforts are part of broader applications in biolubricant niche market.

Market conditions for biolubricants have become favorable in recent years giving increasing environmental awareness and stringent regulations on greenhouse gas emission reduction. With emerging applications, biolubricants have expanded into new markets. The automotive industry, particularly electric vehicles, is a major driver of this growth (Syahir et al., 2017). Electric vehicle manufacturers use biolubricants to enhance the performance and longevity of their components. Additionally, biolubricants are utilized in battery energy storage systems, where they play their role in dissipating heat and maintaining stable operating temperatures.

Biolubricants are compatible with emerging applications in a modern economy. Biolubricants are well-suited for use in hydraulic systems, where their biodegradability and lower toxicity offer significant environmental benefits (Kamyab et al., 2024). In the renewable energy sector, lubricants are used in wind turbines due to their superior performance and longer service life, contributing to reduced maintenance costs (Cecilia et al., 2020). The marine and aviation industries also benefit from biolubricants as their reduced environmental impact aligns with stringent regulations and sustainability goals (Basu et al., 2020). In forestry and agricultural machinery, biolubricants provide enhanced lubrication under harsh operating conditions (Perera et al., 2022).

Eco-labeling programs have been developed to systematically classify various bio-based products, including biolubricants. Biolabeling serves as a certification indicating that the lubricant is derived from renewable biological sources and meets specific environmental standards and social criteria.

Multiple organizations have developed eco-labeling programs for biolubricants with various standards and certification systems. The European Commission's European Ecolabel sets stringent criteria for biodegradability, renewable content, toxicity, and performance. Within Europe, Germany establishes a separate biolubricant labeling system known as Blue Angel (The German Ecolabel, German Federal Environmental Agency, 1978). The Swedish Standards Institute establishes the Swedish Standard SS 155434 for environmental requirements for hydraulic oils, including biolubricants (Swedish Standard Hydraulics -SS155434, Swedish Institute for Standards, 2000). In addition, the Nordic Swan Ecolabel was introduced by the Nordic Council of Ministers. As an official sustainability ecolabel for products from the Nordic countries, Nordic Swan Ecolabel sets rigorous environmental and health criteria for biolubricants (Nordic Swan Ecolabel, The Nordic Council of Ministers, 1989). In the United States, the BioPreferred Program is developed by the United States Department of Agriculture. This BioPreferred Program certifies biolubricants with specified bio-based content and promotes the use of renewable biological ingredients (BioPreferred Program, United States Department of Agriculture, 2002).

Other large and dynamic economies such as China, Japan, and South Korea also have definitions for the use of the biodegradable term when applying for ecolabels. China has established a public voluntary ecolabel scheme, managed by Ministry of Ecology and Environment. The program is to provide an avenue for public participation in choosing and identifying environment-friendly products to promote green consumption (Standard profile for China Environmental Labeling, China environmental labeling program, 1994). Japan has developed an ecolabeling and certification system known as Eco Mark. Eco Mark is managed by the Japan Environment Association. Eco Mark criteria are based on lifecycle thinking and four priority areas including resource conservation, energy efficiency, waste reduction, pollution prevention, and the use of environmentally friendly materials (Eco Mark Program, Japan Environment Association, 1989). South Korea focuses on promoting eco-friendly products enforced by the Ministry of Environment and Korea Environmental Industry and Technology Institute. This certification evaluates biolubricants and other products based on their environmental impact, encouraging manufacturers to adhere to sustainable practices and reduce carbon footprints (Korean Eco-Label Program, Korea Environmental Industry and Technology Institute, 1992).

Europe is considered to be the most mature biolubricant markets over the world, followed by the United States (Nadia and Jumat, 2021). In Europe, the stringent regulations are set forth by entities such as the European Union's REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) (REACH, 2007). REACH is the principal legislation for safeguarding human health and the environment from potential chemical risks. Under REACH, chemical manufacturers and importers are responsible for managing and identifying the risks associated with the substances they bring to the market. They are required to collect data on the properties of their chemical substances and register this information in a centralized database managed by the European Chemicals Agency.

In the United States, the United States Department of Agriculture creates the original food-grade designations H1, H2, and H3 based on their potential contact with food (Original food grade lubricant designations, United States Department of Agriculture, 1882). H1 lubricants are used in food-processing environments where there is the possibility of incidental food contact with a limit of 10 ppm for lubricant base oils, e.g., mineral oil. H2 lubricants are food-grade lubricants used on equipment and machine parts in locations where there is no possibility of contact. H3 lubricants are food-grade lubricants, typically edible oils, used to prevent rust on hooks, trolleys, and similar equipment. As a result, Europe and the United States lead the global market in the development and utilization of biolubricants, setting benchmarks for other regions to follow. In Australia, standards for biolubricants mainly rely on the European Ecolabel and the United States Department of Agriculture's BioPreferred Program to guide the use and development of biolubricants.

5. Future outlook

Microalgae-based biolubricants hold significant promise for applications in modern life. However, the production of biolubricants from microalgal currently remains too costly with existing microalgal strains, cultivation, harvesting, and extraction techniques. There is an urgent need for further research in scaling up lipid/polysaccharide-enriched biomass production, minimizing harvesting costs, and scaling up lipid/ polysaccharide extraction. These research gaps need to be done to enhance the economic viability and sustainability of the biolubricant production process.

Standardizing biolubricant characterization and labeling is also crucial for ensuring product consistency, reliability, and consumer trust. A consistent system enables better comparison and evaluation of the performance and environmental impact of different biolubricants. This will facilitate decision-making for both manufacturers and consumers, promote transparency in the market, and encourage the adoption of sustainable practices. Additionally, standardized labeling can enhance regulatory compliance and support international trade.

The future market share of biolubricants is anticipated to expand, potentially reaching up to 10 % of the total lubricant market by 2030. This growth may be driven by modern industry and the wide use of electric vehicles, which demand specialized, environmentally friendly lubricants. Consequently, manufacturers are anticipated to make significant investments in the research and development of biolubricants to meet the expected demand.

6. Conclusions

Lubricants are essential in the modern economy for controlling friction and temperature increase across many industries. Microalgae-based biolubricants are renewable, biodegradable, and produces lower greenhouse gas emissions than lubricants from petroleum. This review systematically analyses and compares recent data from the literature to reconstruct the current progress of microalgal-based biolubricants. Data and information corroborated in this study affirm the technical feasibility and potential economic outlook of microalgae-based biolubricants. Large-scale and low-cost biomass production is arguably the single most important research priority to commercially realize microalgal-based biolubricants at scale. Green extraction technology requires further research to optimize efficiency while minimizing the use of solvents and environmental damage. The synthesis of microalgae-derived lipids into biolubricants is well-developed and effectively applied; however, additional studies should explore polysaccharides as another valuable component for biolubricant conversion. Further research should also focus on improving tribological performance to achieve good thermo-oxidative stability. Last but not least, efforts are needed to standardize biolubricant characterization and labeling for global marketability.

CRediT authorship contribution statement

Duong T. Nguyen: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Md Abu Hasan Johir:** Writing – review & editing, Visualization, Formal analysis. **T.M. Indra Mahlia:** Writing – review & editing, Validation, Formal analysis. **A.S. Silitonga:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Formal analysis. **Xiaolei Zhang:** Writing – review & editing, Investigation, Formal analysis. **Qiang Liu:** Writing – review & editing, Funding acquisition, Conceptualization. **Long D. Nghiem:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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