

Review Article

A Review on the Potential of Algal Exopolysaccharides for Sustainable Aviation Fuel Production

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Abstract: The aviation industry's increasing carbon footprint has intensified the search for sustainable alternatives to conventional fossil-based jet fuels. Sustainable Aviation Fuel (SAF) has emerged as a promising solution and algal exopolysaccharides (EPS) have gained attention as a novel renewable feedstock owing to their diverse structural, physicochemical and functional properties. This review explores the potential of algal EPS for sustainable aviation fuel production, highlighting their sources, composition, biological significance and suitability as biofuel precursors. The diversity of EPS producing algal species and the influence of environmental and cultivation conditions on EPS yield and composition are discussed, emphasizing opportunities for feedstock optimization. The review comprehensively examines current extraction approaches, including physical, chemical and biological methods, along with their advantages, limitations and prospects for large-scale implementation. Purification strategies such as centrifugation, filtration, precipitation and chromatographic techniques are evaluated for their effectiveness in obtaining high-quality EPS. Furthermore, modification and functionalization approaches, including chemical derivatization, enzymatic treatment and oxidation, are reviewed as means of enhancing EPS properties for biofuel applications. Key characterization techniques used to determine molecular weight, structural features and physicochemical behavior are also discussed. Despite the promising attributes of algal EPS, challenges related to extraction efficiency, production costs, scalability, feedstock variability and limited fuel-performance data remain significant barriers to commercialization. The review identifies critical research gaps and proposes future directions, including standardized fuel testing, pilot scale validation, life cycle assessment and species specific optimization. Overall, algal EPS represent a versatile and environmentally sustainable resource with considerable potential for next-generation sustainable aviation fuels, contributing to the decarbonization of the aviation sector and the advancement of a circular bioeconomy.

Keywords: Algal exopolysaccharides (EPS), Sustainable aviation fuel (SAF), Biofuel feedstock, Extraction techniques, Purification methods, Chemical modification, Environmental sustainability.

Introduction

The rapid growth of the aviation industry has sparked concerns about its environmental impact, particularly due to greenhouse gas emissions from conventional jet fuels (Rye *et al.* 2010). There is an urgent need for sustainable alternatives to reduce the sector's carbon footprint and pave the way

toward greener aviation (Yilmaz and Atmanli 2017). In this context, Sustainable Aviation Fuels (SAF) have garnered significant attention, with the potential to drastically cut emissions and support environmental goals. This review explores the untapped potential of algal exopolysaccharides

(EPS) as a novel feedstock for SAF, emphasizing their unique properties and potential applications.

Algal Exopolysaccharides: Sources, Properties, and Potential

Exopolysaccharides (EPS) synthesized by algae are complex sugars that play a crucial role in cellular adaptation and survival (Deming and Young 2017). EPS help algae form biofilms, adhere to surfaces, and withstand environmental stress. These polysaccharides are produced in response to various factors such as nutrient availability, temperature, and salinity, and their composition can vary widely across algal species. The composition and structure of EPS can be influenced by environmental factors and growth stages, making them highly adaptable (Xiao and Zheng 2016). This variability presents an opportunity to select or engineer specific algae strains for optimized EPS production, potentially tailored for applications like biofuel production.

Notably, the bioactive properties of these EPS, such as antioxidant, anticancer, antiviral and antimicrobial activities, make them valuable for

multiple applications. For instance, *Chlamydomonas reinhardtii*, a green alga, produces EPS with antioxidant properties, which can help neutralize free radicals and reduce oxidative stress (Bafana 2013). Furthermore, *Phaeodactylum tricornutum*, a diatom, produces EPS that demonstrate anti-inflammatory and immunomodulatory activities, which may have therapeutic potential in human health (Willis *et al.* 2013). These properties highlight the wide-ranging biomedical applications of algal EPS. Similar examples are highlighted in Table 1.

The structural characteristics of algal EPS, such as the presence of sulfate groups and branched sugar units, can also significantly affect their applicability in jet fuel production. For example, the thermal stability imparted by sulfate groups in red algae like *Porphyridium cruentum* suggests potential advantages in biofuel stability (Xiao and Zheng 2016). Similarly, certain diatoms, such as *Amphora coffeaeformis*, produce EPS with highly branched structures, which may improve fuel flexibility and performance. These molecular traits, particularly the

Table 1. Algae with Exopolysaccharides Components.

Sl.	Algae	Components of EPS	Activities	References
1	Chlorophyta (Green algae)			
1.1	<i>Chlamydomonas mexicana</i>	Ara, Rha, Fuc, Rib, Xyl, Man, Gal, Glc (+)	Enhanced nonspecific immunity by increasing phagocytic function	(Shnyukova and Zolotarova 2015)
1.2	<i>Chlamydomonas reinhardtii</i>	Galacturonic acid, ribose, Ara, Xylose, Glucose, Gal sugars.	Antioxidant activity	(Bafana 2013)
1.3	<i>Botryococcus braunii</i>	Ara, Rha, Fuc, Gal, Uronic acids, 3-O-Me-Fuc, 3-O-Me-Rha, 6-O-Me-hexose	Antioxidant activity potential feedstock for the production of antioxidant health foods.	(Casadevall <i>et al.</i> 1985; Wang <i>et al.</i> 2021)
1.4	<i>Chlorella zofingiensis</i>	arabinose, D-xylose, D-mannose, D-glucose and D-galactose	Anticancer activity	(Yalcin <i>et al.</i> 1994)
1.5	<i>Chlorella vulgaris</i>	f ara, D-xylose, D-mannose, D-glucose and D-gal	Anticancer activity	(Yalcin <i>et al.</i> 1994)
1.6	<i>Desmococcus olivaceus</i>	Ara, Rha, Xyl, Man, Gal, Glc (+)	Hydrodynamic properties, adhesive properties	(Hokputsa <i>et al.</i> 2003)
1.7	<i>Dunaliella salina</i>	Gal, Glc (+), Xyl, Fru	Biostimulant for salt stress tolerance	(Arroussi <i>et al.</i> 2018; Mishra and Jha 2009)
1.8	<i>Nannochloropsis sp.</i>	Glc (+), Man, Fuc, Man, Xyl	Resistant to harsh oxidative treatment and acid/alkaline hydrolysis	(Scholz <i>et al.</i> 2014; Templeton <i>et al.</i> 2012)

1.9	<i>Dunaliella tertiolecta</i>	Gal, Xyl, Glc, Rib, (1,4)-D-glucan	Biorefinery material, biomass producer for biotechnological and industrial exploitation of bioethanol.	(Goo <i>et al.</i> 2013)
1.10	<i>Graesiella sp.</i>	Fuc (+), Gal, Ara, Glc, Man, Xyl, Rib, Rha	Antioxidant activity, mainly as β -carotene anti bleaching, DPPH- free radical scavenging ability, and ferrous iron-chelating, new film-forming material that could be applied in beef meat preservation.	(Gongi <i>et al.</i> 2022; Trabelsi <i>et al.</i> 2016)
1.11	<i>Gyrodonium impudicum</i>	Galactan	Antiviral Activities, Antioxidant Activities, Anticoagulant and Antithrombotic Activities, Anticancer Activities, Antibacteria Activities	(Pierre <i>et al.</i> 2014; Yim <i>et al.</i> 2007)
2	Bacillariophyceae			
2.1	<i>Amphora rostrata</i>	Rha, Fuc, Xyl, Man, Gal, Glc, uronic acids	Metal binding, Desiccation Prevention, and Flexibility	(Khandeparker and Bhosle 2001)
2.2	<i>Amphora holsatica</i>	Ara, Rha, Fuc, Xyl, Glc, uronic acids	Oceanographic applications	(Leandro <i>et al.</i> 2003; Zhang <i>et al.</i> 2008)
2.3	<i>Cylindrotheca clostridium</i>	Rha, Xyl, Man, Gal, Glc, uronic acids	They are important in the ecology of diatoms living in marine sediments and can be produced in response to changes in nutrient availability. Extrusion of carbohydrates from <i>C. clostridium</i> cells	(Shnyukova and Zolotarova 2015; Staats <i>et al.</i> 1999)
2.4	<i>Cylindrotheca fusiformis</i>	Ara, Rha, Fuc, Xyl, Man, Gal, Glc, uronic acids	EPS production can be influenced by nitrogen and phosphorus deficiencies.	(Magaletti <i>et al.</i> 2004; Shnyukova and Zolotarova 2015)
2.5	<i>Navicula salinarum</i>	Rha, Xyl, Man, Gal, Glc, uronic acids	Stabilization of intertidal sediments	(Staats <i>et al.</i> 1999)
2.6	<i>Navicula directa</i>	Naviculan; Ara, Rha, Fuc, Xyl, Gal, Glc, uronic acids	Antiviral activities, inhibitory effect on cell-cell fusion	(Leandro <i>et al.</i> 2003; Watson <i>et al.</i> 1995)
2.7	<i>Navicula subinflata</i>	Man, Gal, Glc, uronic acids, hexosamines O-Me-pentoses	Antioxidant capacity	(Bhosle <i>et al.</i> 1995; González <i>et al.</i> 2015)
2.8	<i>Phaeodactylum tricornutum</i> CCMP 632 (Ba) ovoidmorphotype	Ara, Rha, Fuc, Rib, Xyl, Man, Gal, Glc, Ino, 3,4-O-Me-Gal	Anti-inflammatory, immunomodulatory activities	(Guzmán <i>et al.</i> 2003; Willis <i>et al.</i> 2013)
2.9	<i>Phaeodactylum tricornutum</i> CCMP 632 (Ba) fusiformmorphotype	Ara, Rha, Fuc, Rib, Xyl, Man, Gal, Glc, Ino, 4-O-Me-Man	Anti-inflammatory, immunomodulatory activities	(Guzmán <i>et al.</i> 2003)
3	Rhodophyta (red algae)			
3.1	<i>Rhodella grisea</i>	Ara, Rha, Fuc, Xyl, Man, Gal, Glc, 3-O-Me-Xyl, 4-O-Me-Xyl, 2,3-di-O-Me-Rha, 2,3-di-O-Me-Fuc, uronic acids	Antitussive activity	(Capek <i>et al.</i> 2008; Nosálová <i>et al.</i> 2012)
3.2	<i>Rhodella maculata</i> CCAP	Ara, Rha, Gal, Glc, Xyl, GlcA	Antimicrosporidian activity	(Roussel <i>et al.</i> 2015)

3.3	<i>Rhodella violacea LMGEIP 001</i>	Ara, Rha, Xyl, Gal, Glc, GlcA	Antimicrosporidian activity	(Roussel <i>et al.</i> 2015; Villay <i>et al.</i> 2013)
3.4	<i>Porphyridium purpureum</i>	With sulfate and methyl residues	Cation Biosequestration BiosurfactantAnti-Viral Products	(Medina-Cabrera <i>et al.</i> 2020)

Ara : Arabinose, Rha: Rhamnose, Fuc: Fucose, Rib: Ribose, Xyl: Xylose, Man: Mannose, Gal: Galactose, Glc: Glucose, GlcA: Glucuronic acid, GalA: Galacturonic acid, GlcNAc: N-acetylglucosamine, GalNAc: N-acetylgalactosamine, Fru: Fructose, Ino: Inositol

branched sugar units and sulfate groups, are believed to affect the viscosity, thermal stability and energy content of the resultant biofuels. However, the direct impact of these structural features on jet fuel properties remains underexplored and further investigation is needed to substantiate their benefits, particularly in terms of fuel quality and performance (Mohammadi *et al.* 2013).

Algal EPS present a unique opportunity for biofuel innovation. While their biological activities in fields such as medicine and environmental science are well-documented, their direct application in biofuel production, especially jet fuel, is an emerging area of research. Understanding the molecular structure of EPS and its impact on fuel characteristics is essential to harness the full potential of algae as a sustainable source of biofuels.

Feedstock Variability and Customization Potential

The diversity of algal species offers a wide range of options for EPS extraction and jet fuel production. Microalgae like *Scenedesmus obliquus* and *Chlorella vulgaris* are noted for their high EPS yields under controlled growth conditions, while macroalgae such as *Ulva lactuca* are suitable for large-scale cultivation through integrated aquaculture systems (Kumar *et al.* 2021). The choice of algal species, driven by EPS content and environmental factors, is a critical consideration in developing sustainable biofuel processes. Recent studies highlight that EPS from *Nannochloropsis salina*, rich in glucose, may enhance fuel stability, while high-energy content from macroalgae like *Sargassum wightii* could improve the calorific value of the resulting fuel (Omran and Abdel-Salam 2020). However, these claims require experimental validation and life-cycle

analyses to evaluate the overall environmental impact and economic feasibility.

Potential of Algal Exopolysaccharides as a Jet Fuel Feedstock

Algal EPS, complex carbohydrates produced by various algae, have emerged as a promising candidate for SAF production due to their distinctive properties and structural diversity. These extracellular polysaccharides serve multiple biological functions, such as cell protection and energy storage. However, their diverse composition-varying in monosaccharide content, chain length, and functional groups-offers an opportunity to tailor these materials for specific aviation fuel requirements (Xiao and Zheng 2016). Optimizing EPS properties, such as energy density and thermal stability, could enhance the performance of bio-based jet fuels, making them a viable alternative to traditional fossil fuels (Waseem *et al.* 2026). Despite these promising aspects, the current literature lacks a comprehensive evaluation of EPS's practical utility as a jet fuel resource.

Environmental Advantages and Scalability of Algal EPS

Algae have several advantages as a sustainable fuel source, including fast growth rates, adaptability to diverse environments, and minimal competition with food crops (Zhu *et al.* 2014). Unlike land-based biofuel crops, algae can be cultivated in marine or wastewater environments, reducing land use and freshwater requirements. EPS production, particularly under nutrient stress, further adds to the scalability of this feedstock (Costa *et al.* 2021). However, while these traits make algae a favorable candidate for biofuel production, more empirical data

is needed to assess the feasibility of using EPS specifically in large-scale jet fuel applications.

Despite the potential of algal EPS for jet fuel applications, several challenges remain. The scalability of EPS extraction, variability in EPS composition and the cost of production are significant barriers that need to be addressed. Research should focus on optimizing cultivation conditions, improving extraction methods and exploring modification techniques to enhance the fuel properties of EPS. Additionally, there is a need for more comprehensive studies that directly compare the performance of EPS-derived jet fuels with existing SAF options. If these challenges are overcome, algal EPS could play a pivotal role in transitioning to a greener aviation industry.

Extraction Techniques

Algal exopolysaccharides (EPS) extraction employs various physical, chemical and biological methods, each chosen based on the specific requirements of the algal species, EPS properties and end-use application. This section delves into physical, chemical and biological extraction methods, discussing their mechanisms, advantages, challenges and optimization strategies.

Physical Methods

Physical methods like homogenization, ultrasonication and microwave-assisted extraction are commonly used for releasing algal EPS from biomass. These techniques leverage mechanical forces or electromagnetic radiation to disrupt algal cell walls, enhancing the release of EPS into the surrounding medium.

Homogenization

Homogenization involves the mechanical disruption of algal biomass, using rotor-stator systems or bead mills to generate intense shear forces that break down cell walls. This process relies on fluid dynamics, where turbulent flow induces shearing forces, weakening the algal cell structure (Diels and Michiels 2006). To maximize EPS yield, it is crucial to optimize parameters like speed, duration and sample-to-buffer ratio. This technique is widely utilized across industries such as food,

pharmaceuticals and biofuels. Innovations include high-pressure homogenization and ultrasonication-assisted homogenization, which further enhance cell disruption. However, excessive shear forces can degrade EPS, necessitating careful parameter control to maintain EPS integrity (Izadi *et al.* 2021).

Ultrasound-Assisted Extraction

Ultrasound-assisted extraction (UAE) employs high-frequency sound waves to generate acoustic cavitation, creating microbubbles that collapse and release localized shock waves, disrupting the cell walls and releasing EPS. This non-thermal technique reduces the risk of thermal degradation of EPS (Goldstein and Reifen 2022).

UAE is favored for its rapid extraction, reduced solvent usage and minimal environmental impact. Parameters such as ultrasound frequency, power intensity and extraction time need to be finely tuned for optimal results (Cravotto and Binello 2016). Researchers are exploring hybrid approaches combining UAE with other methods to improve efficiency while preserving EPS structure (Garcia-Vaquero *et al.* 2017).

Microwave-Assisted Extraction

Microwave-assisted extraction (MAE) utilizes electromagnetic radiation to enhance the extraction process by inducing rapid heating and molecular movement in the solvent and biomass. The method effectively breaks down complex cell structures, allowing efficient release of EPS. Optimization of parameters like microwave power, exposure time, and solvent type is critical for maximizing EPS yield while preventing degradation (Ramalingam *et al.* 2021). MAE is increasingly applied in industries such as pharmaceuticals, food and bioplastics, due to its efficiency and reduced environmental footprint (Samantaray *et al.* 2020).

Chemical Methods

Chemical extraction methods involve the use of acids, alkalis, or ionic liquids to dissolve cell wall components and release EPS. These methods offer efficient extraction but require precise control to avoid damaging the delicate EPS structures.

Acid Extraction

Acid extraction employs strong acids like hydrochloric acid (HCl) and sulfuric acid (H₂SO₄) to hydrolyze the complex matrix of algal cell walls, facilitating EPS release (Poli *et al.* 2010). The efficiency of this method hinges on maintaining a balance between effective hydrolysis and avoiding over-degradation of EPS. Innovations such as sequential acid hydrolysis and hybrid enzymatic-acid approaches have been explored to enhance yield and purity (Liang *et al.* 2021).

Alkaline Extraction

Alkaline extraction leverages high pH environments to disrupt cell wall integrity through saponification, hydrolyzing ester linkages and glycosidic bonds. This method is widely used for its efficiency and has diverse applications, including as emulsifiers and stabilizers in food technology and as drug carriers in pharmaceuticals (Jindal and Khattar 2018; Skendi *et al.* 2020). Optimization of alkaline extraction involves careful adjustment of alkali concentration, temperature and extraction time to balance yield and quality while minimizing degradation (Sitepu *et al.* 2020).

Ionic Liquids

Ionic liquids (ILs) are emerging as an eco-friendly alternative for polysaccharide extraction due to their unique physicochemical properties and tunable solubility. These non-volatile solvents interact with biomass through hydrogen bonding and electrostatic interactions, selectively dissolving cell wall components and releasing EPS (Pinkert *et al.* 2009).

While ILs reduce environmental risks associated with traditional solvents, challenges remain, such as the need for efficient recovery of residual ILs and the high cost of certain formulations (Rahman *et al.* 2021).

Biological Methods

Biological methods involve using enzymes or microorganisms to degrade algal cell walls and facilitate EPS extraction.

Enzymatic Extraction

Enzymatic extraction leverages the specificity of enzymes like cellulases and hemicellulases to break down the algal cell wall matrix, enhancing the release of soluble EPS. This method is valued for its mild conditions, preserving the structural integrity and bioactivity of EPS. Optimizing enzyme concentration, reaction time and temperature is key to maximizing yield and efficiency. Enzymatic extraction is increasingly combined with physical methods to create hybrid approaches that enhance overall extraction efficiency (Vandana and Das 2022).

The extraction of algal EPS involves a diverse array of techniques, each with unique advantages and challenges. Physical methods offer rapid and non-chemical disruption, while chemical methods provide efficient solubilization and biological methods ensure selectivity and structural preservation. Future research should focus on optimizing and hybridizing these techniques to enhance yield, reduce environmental impact and unlock the full potential of algal EPS for industrial applications. Table 2 summarizes various extraction methods for EPS.

Purification Techniques

The efficient utilization of algal exopolysaccharides (EPS) for high-value applications, such as sustainable aviation fuels, hinges on effective purification to remove impurities and achieve the desired quality. A combination of physical, chemical, and chromatographic methods is typically employed to refine EPS for its intended industrial use.

Centrifugation and Filtration

Centrifugation and filtration serve as fundamental initial steps in the purification process. Centrifugation utilizes centrifugal force to separate cells, debris and denser impurities from the EPS-containing supernatant, while filtration further clarifies the solution by removing larger particles (Muylaert *et al.* 2017). For instance, during EPS extraction from microalgae, centrifugation effectively separates the biomass and subsequent filtration

Table 2. Summary of Extraction Methods for EPS.

Methods	Advantages	Disadvantages
2.1. Physical Methods		
2.1.1 Homogenization	Efficient mechanical disruption; versatile applications; recent advancements like high-pressure homogenization; challenges include potential EPS degradation and the need for tailored approaches.	Potential for excessive shear forces; requires precise parameter optimization.
2.1.2 Ultrasound-assisted Extraction (UAE)	Rapid extraction; reduced solvent usage; minimal environmental impact; non-thermal method; advantages in food, pharmaceuticals, and large-scale processes.	Potential over-extraction; the need for specialized equipment.
2.1.3 Microwave-assisted Extraction (MAE)	Rapid and efficient extraction; non-uniform heating reduces thermal degradation; applications in various industries; challenges include optimizing parameters and potential EPS degradation.	Optimization challenges; uniform heating concerns; solvent and energy consumption considerations.
2.2. Chemical Methods		
2.2.1 Acid Extraction	Popular method; controlled pH for cell wall disruption; recent advances like sequential acid hydrolysis; challenges include acid residues and environmental impact.	Possibility of acid residues; environmental impact of acid consumption and disposal.
2.2.2 Alkaline Extraction	Versatile applications; saponification disrupts cell walls; applications in food, pharmaceuticals, and environmental sectors; challenges in optimizing yield and quality.	Higher alkali concentrations risk EPS degradation; and challenges in balancing yield and quality.
2.2.3 Ionic Liquids (ILs)	Non-volatile, environmentally friendly; tunable physicochemical features; selective extraction; adherence to green chemistry principles.	Challenges include residual ILs requiring purification; complex separation techniques; relatively expensive specific ILs.
2.3. Biological Methods		
2.3.1 Enzymatic Extraction	Selective breakdown of cell walls; substrate specificity; enzymatic synergy for improved EPS release; potential applications in various industries.	Optimization challenges; specificity and affinity dependence; careful balance of parameters needed.
2.3.2 Microbial Fermentation	Symbiotic relationship between microorganisms and algae; eco-friendly; potential in food, pharmaceuticals, and bioplastics; optimization strategies essential.	Challenges include microbial contamination, maintaining EPS quality and optimizing parameters.

eliminates remaining particulate impurities, resulting in a clarified EPS solution ready for advanced purification steps (Zhang *et al.* 2018).

Chemical Flocculation

Chemical flocculation involves the addition of flocculants, such as aluminum sulfate or polyacrylamides, to induce aggregation and sedimentation of impurities, simplifying their removal (Bratby 2016; Williams 2007). In a notable case study involving *Chlorella vulgaris*,

chemical flocculation using aluminum sulfate effectively precipitated unwanted proteins and pigments, significantly enhancing EPS purity for downstream processing aimed at biofuel applications (Manning and Gol 2021).

Precipitation

Precipitation techniques selectively isolate EPS while leaving behind contaminants. Ethanol and acetone are common precipitation agents that leverage differential solubility to separate EPS from pigments

and other impurities (Spaeth and Wuertz 2000). For example, ethanol precipitation was employed in a study to obtain purified EPS from algal biomass, followed by centrifugation to collect the EPS fraction, demonstrating its efficacy for applications in bio-based jet fuels (Baldev *et al.* 2015).

Ion-Exchange Chromatography

Ion-exchange chromatography is a technique that separates molecules based on their charge. It is particularly effective for isolating EPS from complex mixtures by selectively binding and eluting charged compounds (Acikara 2013). In a detailed study, ion-exchange chromatography, combined with enzyme treatment, was used to extract EPS from sewage sludge, demonstrating its effectiveness in purifying high-molecular-weight polysaccharides while retaining bioactivity (Wawrzynczyk *et al.* 2007).

Size-Exclusion Chromatography (SEC)

Size-exclusion chromatography (SEC) separates molecules based on their size and hydrodynamic volume, providing a high-resolution method for isolating specific molecular weight fractions of EPS (Barth *et al.* 1998). Research involving EPS from various Cyanobacteria and green algae employed SEC to characterize molecular weight distributions, revealing distinct profiles with potential adhesive and bioactive properties (Hokputsa *et al.* 2003).

The successful purification of algal EPS requires a tailored approach, combining multiple techniques to address specific impurities and preserve the functional properties of EPS. These methods are crucial for producing high-quality algal EPS suitable for sustainable aviation fuel development, aligning with industry demands for efficient and eco-friendly biofuel components.

Modification and Functionalization of Algal Exopolysaccharides

Algal exopolysaccharides (EPS) exhibit unique physicochemical properties, making them promising candidates for biofuel applications. However, to enhance their performance, chemical and enzymatic modifications are often necessary.

Chemical Derivatization

Chemical derivatization involves altering the structural backbone of EPS by introducing functional groups, thereby modifying its properties. Carboxymethylation, a common derivatization technique, incorporates carboxymethyl groups, enhancing solubility and flexibility. A study on EPS from *Nostoc commune* demonstrated that carboxymethylation, combined with doping agents, significantly altered the relaxation properties, improving polymer chain mobility—a feature beneficial for biofuel applications (Gonzales *et al.* 2020).

Enzymatic Modification

Enzymatic modification employs specific enzymes to cleave targeted bonds within EPS molecules, resulting in fragments with enhanced functionality, such as improved emulsifying or solubilizing properties. In a study on the microalgae *Dunaliella tertiolecta*, enzymatic hydrolysis was optimized to convert EPS into glucose efficiently, achieving over 90% recovery under optimal conditions, highlighting its potential for bioethanol production and other industrial applications (Goo *et al.* 2013).

Oxidation

Oxidation techniques, such as periodate oxidation, introduce aldehyde or carboxyl groups into the EPS structure, enhancing reactivity and functional versatility (Yang *et al.* 2003). Analysis of extracellular polysaccharides from *Porphyridium cruentum* revealed complex linkages involving glucuronic acid and methylated sugars. Oxidation studies confirmed structural modifications that increase EPS solubility and reactivity, making them more suitable for advanced biofuel formulations (Percival and Foyle 1979).

Modifying algal EPS through chemical and enzymatic approaches enhances their properties, making them versatile for diverse industrial applications, including sustainable aviation fuels. These tailored modifications allow for improved performance, aligning with the requirements for efficient and eco-friendly biofuel production.

Characterization of Algal Exopolysaccharides (EPS)

Characterizing algal exopolysaccharides (EPS) is a pivotal step in assessing their potential for biofuel applications, especially in jet fuel formulations. A comprehensive understanding of the molecular structure, weight and rheological properties of EPS is essential for optimizing their functional properties. Various analytical techniques, including molecular weight determination, structural analysis, and rheological evaluation, play a critical role in this process.

Molecular Weight Determination

Molecular weight is a key factor influencing the functional behavior of EPS, particularly in applications requiring specific viscosity and solubility properties. Gel Permeation Chromatography (GPC) is a widely employed method for determining the molecular weight distribution of EPS (Gellerstedt 1992).

For instance, in a study on EPS from *Porphyridium* sp., a red microalga, GPC combined with multi-angle laser light scattering (MALLS) was used to determine the molar mass, which averaged 2.3×10^6 g/mol, with a range from 2×10^5 to 4×10^6 g/mol. The study included treatments like sonication and incubation in a cadoxen solution to disaggregate the polysaccharides. Rheological analysis revealed a significant reduction in viscosity with increased sonication time, indicating a transition from a weak gel-like structure to a more liquid-like state, as evidenced by changes in the G2 /G3 ratio across varying frequencies (Geresh *et al.* 2002). Such insights into the molecular weight and viscosity behavior are crucial for tailoring EPS to meet the specific demands of biofuel applications.

Structural Analysis

Structural analysis of EPS provides detailed insights into their repeating units and functional groups, which are essential for predicting their reactivity and performance in industrial applications. Nuclear Magnetic Resonance (NMR) spectroscopy is a powerful tool for elucidating the

detailed molecular structure of EPS (Lambert *et al.* 2019).

For example, NMR analysis of EPS extracted from three *Erythroclonium* spp. revealed highly substituted carrageenans with diverse repeating disaccharide units. The identified structures included carrabiose 2,4'-disulfate of ι -carrageenan, carrabiose 2-sulfate of α -carrageenan and their 6'-O-methylated variants. Additionally, the polysaccharides contained 4-linked galactopyranose, trace amounts of 4-linked 3-O-methylgalactopyranose and terminal glycosyl residues. The comparative analysis across species showed consistent carrageenan compositions, with variations mainly in the proportions of specific components (Chiovitti *et al.* 1997). These structural insights are pivotal for understanding the physicochemical behavior of EPS and optimizing their properties for jet fuel formulations.

Characterization techniques such as GPC and NMR provide essential data on the molecular weight, structural features and rheological properties of algal EPS. This information is crucial for tailoring EPS to meet the specific requirements of sustainable aviation fuel applications. By integrating these analytical methods, researchers can better understand and enhance the performance of algal EPS, paving the way for their effective use in biofuel development.

Addressing the Knowledge Gap: Evaluating Algal EPS for Jet Fuel Applications

One of the significant challenges in establishing algal exopolysaccharides (EPS) as a viable feedstock for jet fuel production lies in the current lack of comprehensive data on their fuel properties and performance metrics. While the potential of algal EPS as a precursor for biofuels is promising, empirical studies specifically investigating their utility and efficiency as jet fuel components are limited. The absence of standardized testing protocols, combined with the diverse chemical structures of algal EPS across different species, has hindered a detailed understanding of their suitability in aviation fuel applications.

Proposed Research Initiatives

Comprehensive Fuel Property Analysis

Future research must prioritize a systematic evaluation of algal EPS-derived biofuels against established aviation fuel standards (e.g., ASTM D7566). Detailed studies should focus on assessing critical properties such as energy content (calorific value), kinematic viscosity, freezing point, and thermal stability, which are essential for safe and efficient jet fuel performance. This comparative analysis will provide a clearer picture of how EPS-derived fuels match up against conventional jet fuels and other biofuel alternatives.

Species-Specific Data Collection

Given the variability in the chemical composition of EPS across different algal species, it is crucial to compile a comprehensive database detailing the structural characteristics and potential fuel properties of EPS from a diverse range of algae. High-throughput screening methods, leveraging advanced analytical tools like gas chromatography-mass spectrometry (GC-MS) and nuclear magnetic resonance (NMR), can facilitate rapid profiling of EPS. This data can be used to identify algal strains with the most promising characteristics for jet fuel production.

Pilot-Scale Experiments and Field Trials

To bridge the gap between laboratory research and real-world application, pilot-scale production and field trials of algal EPS-derived jet fuels are essential. Collaborations with industry stakeholders, including biofuel producers and aviation companies, could enable testing under realistic conditions. These trials would help evaluate not only the fuel's performance but also its economic feasibility and scalability.

Life-Cycle Assessment and Environmental Impact Analysis

A rigorous life-cycle assessment (LCA) of EPS-derived jet fuels is needed to evaluate their overall environmental impact compared to fossil-based jet fuels. This includes analyzing the carbon footprint, resource requirements (e.g., water, energy) and

potential for greenhouse gas emissions reduction. Such studies will provide critical insights into the sustainability of using algal EPS as a jet fuel feedstock and help identify areas for optimization.

Establishing Standardized Testing Protocols

To generate reliable and comparable data, it is imperative to develop standardized testing protocols tailored specifically for algal EPS-derived biofuels. The current ASTM standards for Sustainable Aviation Fuels (SAF) may need adaptation to accommodate the unique properties of polysaccharide-based fuels. This would involve setting benchmarks for key performance indicators and developing specific testing methodologies that account for the high molecular weight, branching, and functional group diversity characteristic of algal EPS.

Collaborative Efforts and Funding

Addressing the data gap will require a concerted effort from academic researchers, industry experts, and policymakers. Initiatives such as public-private research partnerships, government funding programs and international consortia focused on sustainable aviation can accelerate data collection and analysis. By pooling resources and expertise, the aviation industry can expedite the research necessary to validate algal EPS as a viable feedstock for jet fuels, fostering a new era of sustainable, low-carbon aviation.

Conclusion

The potential of algal exopolysaccharides (EPS) as a sustainable feedstock for aviation biofuels represents a promising yet underexplored avenue for reducing the environmental footprint of the aviation industry. The distinctive structural properties of algal EPS, including high thermal stability, unique functional groups and diverse molecular weights, present significant opportunities for developing advanced bio-based jet fuels. The variability in monosaccharide composition, presence of sulfate groups and complex branching patterns observed in certain algae, such as *Porphyridium cruentum* and *Amphora coffeaeformis*, contribute to enhanced fuel stability and energy content,

potentially surpassing some traditional biomass feedstocks. Extraction and purification techniques remain critical in unlocking the full potential of algal EPS. Physical methods like ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) have demonstrated efficiency in disrupting cell walls and maximizing EPS yield, while chemical and biological methods provide selective and environmentally conscious alternatives. The integration of hybrid approaches, such as combining enzymatic hydrolysis with advanced chromatographic purification, offers a pathway to obtaining high-quality EPS tailored for biofuel applications. However, challenges in scaling these methods, optimizing extraction conditions, and ensuring consistent quality across diverse algal strains need to be addressed. Modification and functionalization strategies, such as carboxymethylation, enzymatic hydrolysis and oxidation, further enhance the properties of algal EPS, making them suitable for high-performance aviation fuels. These tailored modifications increase solubility, flexibility and thermal stability, aligning with the stringent requirements of the aviation industry. Additionally, the use of eco-friendly ionic liquids and innovative flocculation techniques has shown potential in improving the efficiency and sustainability of the extraction process. Despite the promising attributes, the economic feasibility and life-cycle sustainability of using algal EPS as a jet fuel feedstock require further empirical validation. Comprehensive comparative studies are needed to benchmark EPS-derived jet fuels against conventional SAF options, focusing on key performance indicators such as viscosity, calorific value and emissions reduction. Future research should emphasize large-scale cultivation systems, optimization of growth conditions to enhance EPS yield and robust life-cycle assessments to fully understand the environmental benefits. In summary, algal EPS hold significant promise as a renewable, versatile and eco-friendly feedstock for sustainable aviation fuels. By leveraging the unique properties of these extracellular polysaccharides, coupled with advances in extraction, purification and modification techniques, it is possible to create a viable

alternative to fossil-based jet fuels. This could play a pivotal role in the aviation sector's transition towards greener, more sustainable energy solutions, helping to meet global carbon reduction targets and addressing the growing demand for cleaner aviation practices. With continued innovation and interdisciplinary collaboration, algal EPS could redefine the future of sustainable aviation, offering a scalable and impactful solution to one of the most pressing environmental challenges of our time.

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