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ADVANCING SUSTAINABLE RESOURCE UTILISATION: A REVIEW OF AQUATIC BIOREFINERIES

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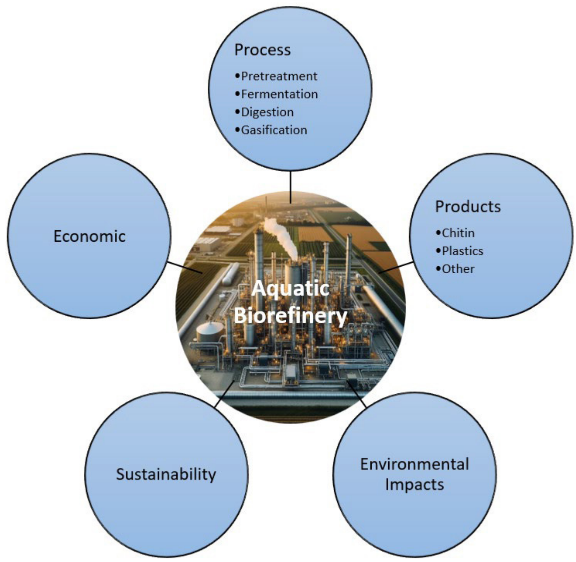
HIGHLIGHTS

- Harnessing the potential of high-lipid algae to produce eco-friendly biofuels propels sustainable energy solutions.
- Derived from crustacean waste, chitin is a versatile resource in transforming various industries.
- Unlocking valuable resources from wastewater streams will pioneer a circular economy approach in aquatic biorefineries.
- Incorporating latest studies, LCA analysis guides the path towards heightened environmental resilience.
- Revolutionising material science, bioplastics from aquatic biomass redefine the landscape of sustainable and eco-friendly alternatives.

GRAPHICAL ABSTRACT



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ABSTRACT

This review explores the transformative potential of aquatic biorefineries in advancing sustainable resource utilisation. As global demands for renewable resources intensify, biorefineries have emerged as versatile solutions. Focusing on aquatic environments, this paper delves into diverse biomass resources, encompassing microorganisms, algae and aquatic plants. It navigates through key biorefinery processes, including hydrothermal liquefaction, algae cultivation and enzymatic conversion, illuminating their roles in sustainable biofuel and high-value chemical production. Thermochemical conversion processes, such as pyrolysis and gasification, offer additional pathways for bio-based product generation. The review critically assesses challenges in these processes, ranging from technical intricacies to regulatory considerations. Examining products derived from aquatic biorefineries (i.e. biofuels, chemicals and biomaterials) underscores their versatility. Looking ahead, the paper identifies technical challenges, regulatory landscapes and emerging technologies as focal points for future research. The review concludes by envisioning aquatic biorefineries as key players in sustainable resource management, advocating for research and technological innovation to propel this transformative field into the mainstream of the bio-based economy.

Introduction

In the face of escalating environmental challenges and the ever-growing demand for renewable resources, the exploration of innovative and sustainable technologies has become imperative (Song & Fisher *et al*., 2019). Biorefineries, as versatile platforms for the conversion of biomass into a spectrum of valuable products, offer a promising solution to address both environmental concerns and the need for alternative resources (Kamm & Kamm, 2004). While terrestrial biomass has been extensively studied, this review focuses on the relatively nascent field of aquatic biorefineries, unlocking the potential of aquatic biomass for sustainable development.

Biorefineries represent a paradigm shift in the utilisation of natural resources, aiming to emulate the efficiency and versatility observed in petroleum refineries. These facilities integrate various conversion processes to extract maximum value from biomass, encompassing a range of feedstock from agricultural residues to dedicated energy crops (Demirbas, 2009). Aquatic biorefineries, in particular, diverge from traditional models by capitalising on the rich biodiversity found in water bodies, presenting a unique avenue for sustainable resource utilisation (Saxena *et al*., 2022).

The global demand for resources, driven by population growth and industrialisation, has placed an unprecedented strain on ecosystems. Traditional resource extraction practices have often led to environmental degradation, loss of biodiversity, and increased greenhouse gas emissions. In this context, the significance of sustainable resource utilisation cannot be overstated. Aquatic biorefineries offer an environmentally friendly alternative, leveraging the regenerative capacity of aquatic ecosystems to produce biofuels, chemicals and materials without compromising ecosystem integrity.

While the concept of biorefineries has gained traction, the potential of aquatic biomass remains underexplored. Aquatic environments, including oceans, lakes and ponds, harbour a diverse array of biomass, ranging from algae and aquatic plants to microorganisms (Moreira, Cruz *et al*., 2022). These resources possess unique biochemical compositions that can be harnessed for the production of biofuels, high-value chemicals and biomaterials. By shifting the focus to aquatic biorefineries, we not only diversify the resource base, but also enhance the overall sustainability of biorefinery processes.

In subsequent sections, the types of aquatic biomass resources, the various biorefinery processes applicable to aquatic environments, and the products derived from these processes are delved into. Furthermore, the environmental and economic sustainability of aquatic biorefineries, a discussion on challenges encountered, and an outline of future prospects for this burgeoning field are presented.

Aquatic Biomass Resources

Aquatic ecosystems house a diverse array of biomass, each with unique properties suitable for biorefinery processes. Algae, for instance, stand out as a prominent aquatic resource due to their rapid growth rates and high lipid content (Schnurr & Allen, 2015). Microorganisms and aquatic plants also contribute to the rich tapestry of aquatic biomass (Amulya, Morris *et al*., 2023). Understanding the characteristics and potential applications of these resources is crucial for optimising biorefinery processes.

Algae, encompassing a wide range of micro and macroscopic organisms, are central to the success of aquatic biorefineries (Trivedi *et al*., 2015). Their ability to thrive in diverse aquatic environments and their efficient conversion of sunlight into biomass make them valuable feedstock for biofuel production. Moreover, algae's rich nutritional profile (Wells *et al*., 2017) and versatility for producing high-value compounds (Koyande *et al*., 2021) position them as key players in the biorefinery landscape.

Beyond algae, bacteria and fungi, as well as aquatic plants, contribute significantly to the biomass available for biorefinery processes. These resources bring additional biochemical diversity, enabling the production of a spectrum of bio-based products. Exploring the untapped potential of microorganisms and aquatic plants expands the scope of aquatic biorefineries, paving the way for novel and sustainable applications.

Biorefinery Processes

Hydrothermal liquefaction (HTL) is a promising biorefinery process that involves the conversion of wet biomass into bio-crude oil under high temperatures and pressure (Shahbeik *et al*., 2024). In aquatic biorefineries, HTL has shown potential for processing algae and other aquatic biomass, providing an efficient method for the production of liquid biofuels. Understanding the mechanisms and optimising HTL for specific aquatic feedstock is critical for enhancing the overall efficiency of aquatic biorefinery operations (Figure 1).

The cultivation and harvesting of algae represent fundamental steps in aquatic biorefinery processes. Phototrophic cultivation systems, such as open ponds and closed photobioreactors, are commonly employed to maximise biomass production. Harvesting methods, including centrifugation, filtration and flocculation, aim to separate algae from the cultivation medium. Innovation in cultivation and harvesting technologies is essential for scaling up production at biorefineries and ensuring their economic viability.

Efficient extraction of valuable compounds from aquatic biomass is a key aspect of biorefinery processes (Esquivel-Hernández *et al*., 2017). Various extraction techniques, such as solvent extraction, supercritical fluid extraction and mechanical methods, are employed to recover lipids, proteins and other bioactive compounds. Optimising extraction processes is crucial for obtaining high yields and maintaining the overall sustainability of aquatic biorefineries.

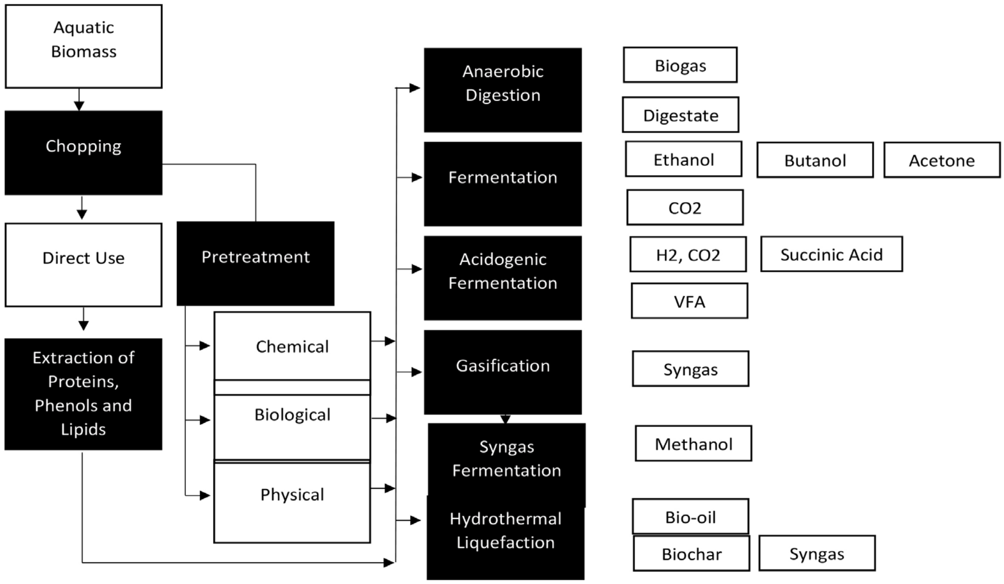
Figure 1: Main processing strategies in aquatic

Biochemical Conversion

Biochemical conversion processes also play a pivotal role in aquatic biorefineries, particularly in the production of biofuels and high-value chemicals. Fermentation, a biological process where microorganisms convert sugars into ethanol (Lee, Oh *et al*., 2011), butanol (Ellis, Hengge *et al*., 2012) or other organic compounds, is a key pathway. Exploring different fermentation strategies, such as anaerobic and aerobic fermentation, offers insights into optimising yield and diversifying the range of bio-based products derived from aquatic biomass (Kaur, Kumar *et al*., 2019).

Enzymatic conversion processes leverage the catalytic properties of enzymes to break down complex biomolecules into simpler, valuable compounds (Kumar & Verma 2020). In aquatic biorefineries, enzymes play a crucial role in hydrolysing algae cell walls or breaking down polymers into fermentable sugars. Understanding the enzymatic pathways involved and developing enzyme cocktails tailored to aquatic biomass composition is essential for enhancing the efficiency and feasibility of enzymatic conversion processes.

Aquatic biomass encompasses a myriad of biochemical constituents, each with unique pathways for conversion (Parakh, Tian *et al*., 2023). Delving into the specific biochemical pathways involved in the transformation of aquatic biomass into biofuels, chemicals, and materials provides a comprehensive understanding of the underlying mechanisms. Identifying key enzymatic reactions and metabolic pathways aids in the design of



biorefineries

engineered microorganisms or processes for targeted and efficient product synthesis.

Thermochemical Conversion

Pyrolysis, a thermochemical conversion process involving the heating of biomass in the absence of oxygen, is a promising avenue in aquatic biorefineries. This process can produce bio-oil, biochar and syngas from aquatic biomass. Investigating the optimal pyrolysis conditions, such as temperature and residence time, is critical for maximising bio-oil yield and tailoring the properties of the resulting products to specific applications.

Gasification, another thermochemical conversion process, transforms biomass into syngas, a mixture of hydrogen and carbon monoxide (Shahbeik *et al*., 2022). In aquatic biorefineries, gasification offers a pathway to produce clean and versatile syngas from algae and aquatic plant biomass. This processing is favoured over traditional biomass gasification technologies due to its distinctive technical, economic, and environmental attributes. The growing multitude of research initiatives focused on this process for transforming wet biomass into high-value products underscores its potential as a promising pathway. Examining different gasification techniques, such as fluidised bed and entrained flow gasification, provides insights into process optimisation and the integration of syngas into existing industrial applications.

While thermochemical conversion processes hold great promise, they also present challenges, including reactor design, feedstock variability and product upgrading. Addressing these challenges is crucial for the successful implementation of aquatic biorefineries. Identifying opportunities for innovation, such as hybrid processes and integrated biorefinery concepts, enhances the overall efficiency and sustainability of thermochemical conversion in aquatic biomass utilization.

Products from Aquatic Biorefineries

One of the primary goals of aquatic biorefineries is the production of sustainable biofuels. Algal biofuels, such as biodiesel and bioethanol, are particularly promising due to the high lipid content of algae (Daroch *et al*., 2013). Investigating the optimisation of cultivation conditions, lipid extraction methods and conversion processes are essential for achieving economically viable and environmentally sustainable biofuel production in aquatic biorefineries.

Aquatic biomass is also rich in valuable compounds beyond biofuels (Zhou *et al*., 2022). Biorefinery processes can extract high-value chemicals, such as pigments (Pangestuti & Kim, 2011), antioxidants (Balboa *et al*., 2013), chitosan (Amiri *et al*., 2022) and omega-3 fatty acids (Adarme-Vega *et al*., 2014), all of which have vital applications in the food, pharmaceutical and cosmetic industries. Exploring the diverse range of compounds present in aquatic biomass and developing efficient extraction and purification methods can open avenues for the production of nutraceuticals and specialty chemicals. Overlooking certain significant products, such as chitin derived from crustacean waste and the recovery of resources from wastewater streams, is a pertinent observation. Chitin, a versatile biopolymer, is extracted from crustacean shells and has diverse applications, including in the pharmaceutical and agriculture industries (Amiri *et al*., 2022). Additionally, the recovery of resources from wastewater streams is an emerging aspect that adds another layer to the sustainability of aquatic biorefineries. These oversights highlight the need for a more comprehensive examination of diverse products that can be derived from aquatic biomass, ensuring a holistic understanding of the potential applications and environmental benefits associated with aquatic biorefinery processes.

The sustainable production of biomaterials and bioplastics is gaining prominence in the quest for eco-friendly alternatives to traditional plastics (Figure 2). Aquatic biomass, with its unique biochemical composition, provides a source for the production of biodegradable materials. Investigating the feasibility of converting aquatic biomass into biopolymers and exploring potential applications in packaging and other industries contribute to the development of sustainable materials in aquatic biorefineries.

Environmental and Economic Sustainability

Assessing the environmental impact of aquatic biorefineries is crucial for determining their overall sustainability. Analysing greenhouse gas emissions, energy consumption and the carbon footprint associated with different biorefinery processes provides insight into its environmental benefits and challenges. Addressing these aspects is essential in ensuring that aquatic biorefineries contribute positively to mitigating climate change and reducing their overall environmental impact. Aquatic ecosystems are sensitive to changes in water usage and quality. Evaluating the water footprint of aquatic biorefineries, including water consumption and wastewater generation, is vital for sustainability.

Understanding the potential environmental impact on aquatic habitats and ecosystems ensures responsible resource management and aligns aquatic biorefineries with principles of ecological sustainability. The economic viability of aquatic biorefineries is a critical factor in their long-term success. Analysing production costs, market trends and potential revenue streams for bio-based products derived from aquatic biomass provides valuable insights for investors and industry stakeholders. Identifying market niches and staying abreast of evolving economic factors contributes to the resilience and growth of the aquatic biorefinery sector.

Challenges and Future Prospects

Despite the promising potential of aquatic biorefineries, several technical challenges must be addressed for successful implementation. These challenges may include optimising cultivation and harvesting techniques, developing efficient extraction methods, and scaling up biorefinery processes (Yadav & Sen, 2018; Nawaj Alam *et al*., 2021). Investigating and overcoming these technical hurdles are essential for advancing the feasibility and competitiveness of aquatic biorefineries.

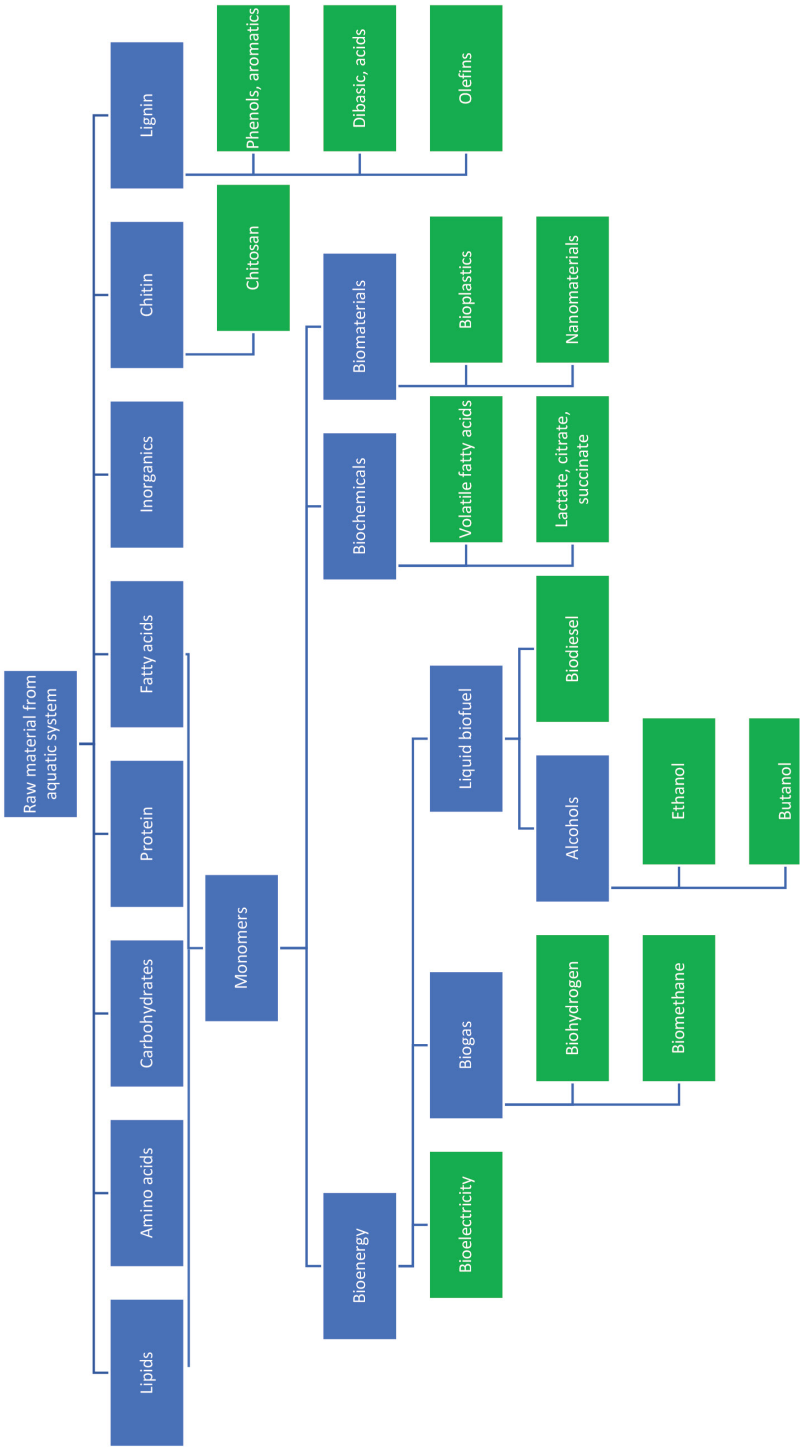


Figure 2: Different biorefinery concepts for valorisation of aquatic waste

The regulatory landscape plays a pivotal role in shaping the future of aquatic biorefineries because it does not evolve as fast as technology (Scholten & Figueirêdo, 2022). Understanding and navigating regulations related to biomass utilisation, waste management and product certification are critical for ensuring compliance and market acceptance. Moreover, policy frameworks that support the development of sustainable biorefinery technologies can significantly influence the growth and integration of aquatic biorefineries into broader energy and industrial landscapes.

The field of aquatic biorefineries is dynamic, with ongoing research and development leading to the emergence of new technologies and approaches. Exploring cutting-edge technologies, such as genetic engineering for biomass improvement (Tabatabaei *et al*., 2011), advanced cultivation systems (Xiaogang *et al*., 2020) and innovative conversion processes (Azwar *et al*., 2022) provides a glimpse into the future of aquatic biorefineries. Identifying key research areas and potential breakthroughs will enhance our understanding of the evolving landscape and guide future research direction. The optimisation of algae harvesting methods, for instance, is one of the challenging stages to enhance overall process efficiency. In recent studies, achieving cost-effective and scalable methods for harvesting microalgae, particularly cationic polymeric flocculant-based harvesting, has been the subject of a number of recent studies (Kumar *et al*., 2023). The choice of harvesting technique significantly impacts the overall economics of algae-based biorefineries. Techniques such as centrifugation, flocculation and filtration present distinct advantages and drawbacks, each influencing the economic viability of the biorefinery process.

Conclusion

In conclusion, this review has explored the diverse landscape of aquatic biorefineries, emphasising their potential for sustainable resource utilisation. An overview of the importance of biorefineries in the context of addressing environmental challenges and meeting the growing demand for renewable resources was presented. Focusing on aquatic biorefineries, the types of aquatic biomass resources, various biorefinery processes and the range of products that can be derived were delved. The future of aquatic biorefineries holds great promise but also presents challenges that demand continued research and innovation. Addressing technical challenges, navigating regulatory landscapes, and staying abreast of emerging technologies will be critical for the continued success and growth of aquatic biorefineries. Research endeavours should focus on improving the efficiency of cultivation, harvesting, and conversion processes, as well as exploring new avenues for product diversification. Aquatic biorefineries offer a sustainable pathway towards resource management by utilising the rich biodiversity of aquatic environments. The production of biofuels, high-value chemicals and biomaterials aligns with the principles of the circular economy and mitigates the environmental impact associated with traditional resource extraction. The implications of adopting aquatic biorefineries extend beyond economic considerations, contributing to the broader goals of environmental sustainability and climate change mitigation. In conclusion, while challenges exist, the potential benefits of aquatic biorefineries are substantial. As research and development in this field progress, it is anticipated that aquatic biorefineries will play a pivotal role in shaping the future of sustainable resource utilisation and contributing to the global transition towards a bio-based economy.

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Conflict of Interest

All authors declare that they have no conflicts of interest.

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