Part 1

Process Fundamentals

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Chapter 1

Algal systems for resource recovery from waste and wastewater

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ABSTRACT

This chapter provides an overview of the book. The introduction highlights the need for algal-based technologies in waste management and resource recovery in order to boost the circular bioeconomy globally. The book is divided into four parts, consisting of twelve chapters in total, which provide a detailed description of topics ranging from process fundamentals to up-to-date information on various modern algal-based technologies for waste remediation, nutrient recovery, and simultaneous energy generation. The book is suitable for students, research professionals and policymakers who are working in the domain of environmental engineering/sciences, wastewater treatment and renewable energy.

As a consequence of the swift proliferation of the global economy and population, the availability of water resources for direct human consumption has become insufficient. Forecasts indicate a projected 40% global water deficit by 2030, which gives rise to critical challenges for both society and economic advancement (Kandasamy *et al.*, 2023). This scarcity is primarily attributed to escalating water demands, the contamination of existing water supplies, and a lack of efficient technologies for water recycling. As a result, the imperative of water remediation is bound to assume a central role on the international stage, demanding urgent attention and action.

Historically, wastewater treatment arising from diverse industries has predominantly relied on the implementation of chemical processes such as flocculation, disinfection, oxidation, and neutralization and physical techniques, including grit chamber, floatation, and screening (Chojnacka *et al.*, 2020; Kurniawan *et al.*, 2022). Despite their widespread use, these chemical and physical treatment methodologies remain financially burdensome and generate substantial volumes of slurry or sludge, thereby requiring supplementary treatment steps. Moreover, the wastewater treatment processes are energetically expensive and demand trained staff for the operation of treatment facilities, which are associated with considerable capital costs for infrastructure development (Kandasamy *et al.*, 2023).

Consequently, scientists and researchers are currently exploring alternative approaches for wastewater treatment and nutrient recovery, centering on the utilization of microalgae. These innovative methods hold the promise of providing an environmentally friendly and sustainable means of treating wastewater, potentially enabling the recovery of nutrients as high as 95% (Moradi & Saidi, 2022). Microalgae growing in wastewater can facilitate the production of biomass, which contains valuable components such as carbohydrates, proteins, lipids, and other valuable biomolecules that can be utilized in the production of third-generation biofuels (Shearian Sattari *et al.*, 2022). Several modes such as open ponds, photobioreactors, and advanced culture systems, are being considered to foster the cultivation of microalgae, offering diverse and promising pathways for their effective implementation (Kandasamy *et al.*, 2023; Khandelwal *et al.*, 2023).

The successful cultivation of microalgae in diverse industrial wastewaters, along with the efficacy of the effluent treatment processes, is contingent upon achieving an optimal nutrient load and composition within the wastewater. In instances where the nitrogen:phosphorus (N:P) ratios in the water are reduced, certain strains of *Cladophora* have demonstrated enhanced efficiency in removing nutrients from the environment (Sandani *et al.*, 2020). On the other hand, algal families characterized by higher N:P ratios, such as *Pseudanabaena*, exhibit more effective nutrient removal capabilities (Kandasamy *et al.*, 2023). Nonetheless, a comprehensive study involving filamentous benthic algae has indicated that for the specific context of municipal wastewater nutrient removal, the optimal N:P ratios should fall within the range of 5:1 to 15:1, 7:1 to 10:1, and 7:1 to 20:1 for *Cladophora*, *Klebsormidium*, and *Pseudanabaena*, respectively (Valchev & Ribarova, 2022). Generally, the various strains of algae do not respond similarly to different N:P ratios, leading to varying impact on their nutrient removal capabilities.

The shift toward a circular bioeconomy, which emphasizes resource diversification, has provided the impetus for transforming conventional wastewater treatment processes capable of handling various waste streams. The transition has gained momentum, and the increasing enthusiasm can be credited to the dynamic and evolving nature of microalgal-based wastewater treatment solutions. Overcoming critical barriers related to nutrient assimilation and achieving increased microalgae growth rates have rendered microalgae-based wastewater treatment a compelling and powerful alternative to traditional methods (Khan *et al.*, 2022). In this context, this book explores the potential applications of algal biomass in wastewater remediation and bioenergy production. The book is divided into the following four parts.

1.1 PROCESS FUNDAMENTALS

This chapter discusses the cultivation of microalgae in wastewater, their metabolic modelling to analyze the growth rate (Chapter 2) and their interaction with bacteria (Chapter 3). To advance sustainable wastewater treatment technology, a comprehensive investigation is proposed, focusing on the symbiotic bacterio-algal relationship (Chapter 3) and the role of quorum sensing signal molecules in shaping the integrated wastewater treatment solution involving both algae and bacterial processes. This segment aims to lay the groundwork for refining algae–bacteria based wastewater treatment methods through various approaches.

These findings are expected to offer valuable insights for promoting sustainable economic and environmental development. Additionally, the utilization of synergistic bacterial–algal wastewater treatment technologies has the potential to contribute toward lowering the carbon emissions (Hena *et al.*, 2021). By combining these approaches, the research endeavors to pave the way for more effective and environment-friendly wastewater treatment practices, with the ultimate goal of fostering sustainable development and mitigating environmental impacts.

Furthermore, the basics of macroalgae-based biorefinery are also discussed in detail (Chapter 4), which makes the book suitable for every phycologist. This part majorly focuses on the following three aspects: (1) metabolic modelling of algal growth using waste as substrate, (2) synergistic approach of algae–bacteria for efficient wastewater treatment and selection of key microalgae and bacterial species in wastewater treatment systems, and (3) use of of macroalgae to produce fertilizers, feed (additives), and other value-added products.

1.2 ALGAL-BASED WASTEWATER TREATMENT

Although the use of microalgae for wastewater treatment was proposed in the last century, the technology was not sufficiently efficient and robust to be applied at a commercial scale. Only recent advances in the knowledge of biological systems, the engineering of the reactors and the harvesting and processing of the produced biomass allow the development of the first industrial demonstrations (Acién *et al.*, 2016). Facilities of several hectares are already in operation demonstrating the feasibility of this technology (Nguyen *et al.*, 2022). However, challenges remain for the further improvement and enlargement of these systems. They are related to (a) the improvement of knowledge and management of the biological system, (b) the development of adequate strategies for the allocation and implementation of large-scale facilities, (c) the definition of optimal operational conditions, including the development of non-assisted systems capable to operate under variable environmental conditions, and (d) the development of adequate routes for biomass valorization (Acién *et al.*, 2016).

Large efforts which are being devoted to solving these challenges and thus to making this technology reliable for industrial applications, are detailed in Chapter 5. Furthermore, possibilities and challenges in coculturing methanotrophs with microalgae for wastewater treatment are discussed in Chapter 6. Part 2 summarizes the status, major challenges, and potential contribution of microalgae-related wastewater treatment processes.

1.3 VALORIZATION OF ALGAL BIOMASS BY INTEGRATING WITH DIFFERENT TECHNOLOGIES

Microalgal systems play a crucial role in shifting the perspective of wastewater from being seen as disposable waste to being recognized as a valuable resource capable of yielding new value-added products. This shift toward a more sustainable approach brings together significant environmental and economic potential, endorsing the principles of a circular economy (Amaro *et al.*, 2023). Through the production of bioenergy and bioproducts, these systems contribute to the energy–environment nexus, paving the way for a sustainable closed-loop economy (Bele *et al.*, 2023).

Given the pressing challenges of global water scarcity and the escalating costs associated with wastewater treatment, numerous research works and government projects have emerged, exploring the application of microalgal systems for wastewater treatment while concurrently extracting valuable biomass resources. Specifically, managing manure poses significant difficulties and expenses for livestock and poultry operations, particularly in cold climate regions (Bele *et al.*, 2023). Addressing these challenges necessitates adopting sustainable approaches to nutrient management, reuse, and recycling, which can not only generate additional income for farmers but also enhance agricultural environmental sustainability.

The integration of green innovations, such as algae cultivation, bioelectrochemical systems (BES), and anaerobic digestion emerges as a key strategy to recover nutrients, complete utilization of manure, and make the overall process more sustainable. Part 3 aims to comprehensively explore the potential of integrating microalgae into the growing biogas and wastewater industry along with the potential of BES for simultaneous waste remediation, algae cultivation, and power generation. It seeks to identify opportunities and challenges inherent in this approach and reviews the prospective bioproducts, such as bioelectricity arising from BES (Chapter 7), biogas (Chapter 8), and bioethanol (Chapter 9). Such integration represents a transformative approach that harnesses the vast untapped potential of waste, aligning with the principles of the circular economy and advancing the sustainable development goals.

1.4 ALGAL BIOTECHNOLOGY

The microalgae biorefinery presents a promising and sustainable solution for producing biofuels and a diverse array of bulk chemical products. Extensive efforts have been dedicated to utilizing microalgae biomass in biorefineries to advance sustainable development, primarily due to their abundant bioactive constituents (Okeke *et al*., 2022). Part 4 provides a comprehensive review of potential strategies aimed at enhancing microalgae biorefinery obtaining high-value-added renewable products (Chapters 10 and 11) and optimizing the transformation of microalgae-based technologies into economically viable products (Chapter 12). The focus is on ensuring the long-term viability of the processes, taking into account both economic feasibility and environmental considerations.

Moreover, ongoing research explores the integration of microalgae biorefineries with other eco-friendly alternatives, such as microalgae-based bioplastics, which opens up new possibilities for synergistic applications (Okeke *et al*., 2022). The microalgae biorefining process holds the promise of becoming a key element of green technology, facilitating the biosynthesis of a broad range of valuable biofuels and biochemical products, further reinforcing the outlook for sustainable and environmentally friendly solutions to recover resources from waste and wastewater.

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