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The industrial ecology of freshwater macroalgae for biomass applications

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ABSTRACT

Industrial ecology is focused on recognising the inherent value in waste streams and developing techniques that can efficiently recover this value. Freshwater macroalgae can become a foundation of this concept as they can be cultured in a range of waste streams where they can effectively remove excess nutrients, metals and metalloids, providing both a bioremediation service and a biomass resource. The cultured algal biomass can then be used as a product in animal feeds, biochar, biosorbents or as a feedstock biomass for the production of bioenergy. Freshwater macroalgae provide a unique opportunity to transform a range of industries through the utilisation of wastewater to produce biomass that can be converted into valuable bioproducts.

1. Introduction

Industrial ecology examines materials and energy flows in products, processes, industries and economies [1,2]. It aims to replicate the efficiencies seen in natural ecosystems and change industrial processes from linear systems, in which resources move through the system in a single direction to produce products and waste products, to systems where wastes are recycled to become inputs for new processes [1,3]. A central focus of industrial ecology is the development of processes and practices that reduce environmental impacts through the beneficial use of waste products as raw material [3] and is an innovative model for economic growth, social development and environmental management [4]. An innovative and developing industrial ecology model is to cultivate macroalgae in wastewater as a bioremediation technology, with the biomass then serving as an input for algal-based end-products such as food, feed, and bioenergy (e.g., [4]). Freshwater macroalgae provide a particularly innovative opportunity across multiple industries due to their ability to grow in a range of wastewaters and the suitability of resultant biomass for a variety of applications (Fig. 1). Our objective is to highlight and review recent research describing the large-scale cultivation of freshwater macroalgae in wastewater and their bioremediation capabilities, and provide an overview of the products which freshwater macroalgae can provide as a by-product of bioremediation. Finally, we demonstrate how freshwater macroalgae can be integrated into an industrial ecology system.

2. Large-scale cultivation of freshwater macroalgae in wastewater

Large-scale cultivation of macroalgae in wastewater has predominantly occurred in algal turf scrubber (ATS) systems or open ponds at the scale of more than 20 kL day^{-1} (Table 1). ATS systems consist of an attached algal community, containing many species of macro- and microalgae and associated microbes and micro-invertebrates, which grows as a turf on screens in a shallow trough through which water is pumped [6]. The most widely used open pond system for large-scale macroalgal cultivation is the High Rate Algal Pond (HRAP) [4,7]. HRAPs are shallow, circular raceways around which water is gently circulated by a paddlewheel, maintaining the macroalgae in constant suspension. In contrast to ATS systems, which have a mixed algal community that is largely self-seeded and uncontrolled (e.g., [8]), HRAPs maintain a monoculture of a single species of macroalgae. This provides the advantage of delivering a consistent composition and source of biomass for bioproducts. Therefore, considerable research effort has focused on the identification of species of freshwater macroalgae for cultivation in outdoor pond systems.

The macroalgal genera *Rhizoclonium*, *Cladophora* and *Oedogonium* have commonly been used for bioremediation [8–10]. However, it is clear that the cosmopolitan freshwater macroalgal genus *Oedogonium* has advantages in open pond systems as it is robust and competitively dominant with a biochemical composition which aligns itself well with a range of biomass applications ([11], Table 2). *Oedogonium* is an ideal candidate for use in an industrial ecology framework as it has high biomass productivities comparable to those of microalgae (~20 g dry weight (DW) m^{-2} day^{-1}) when cultured in a variety of water sources (Table 2), including agricultural and municipal wastewaters rich in nitrogen and phosphorus [9,12,13], and industrial wastewater

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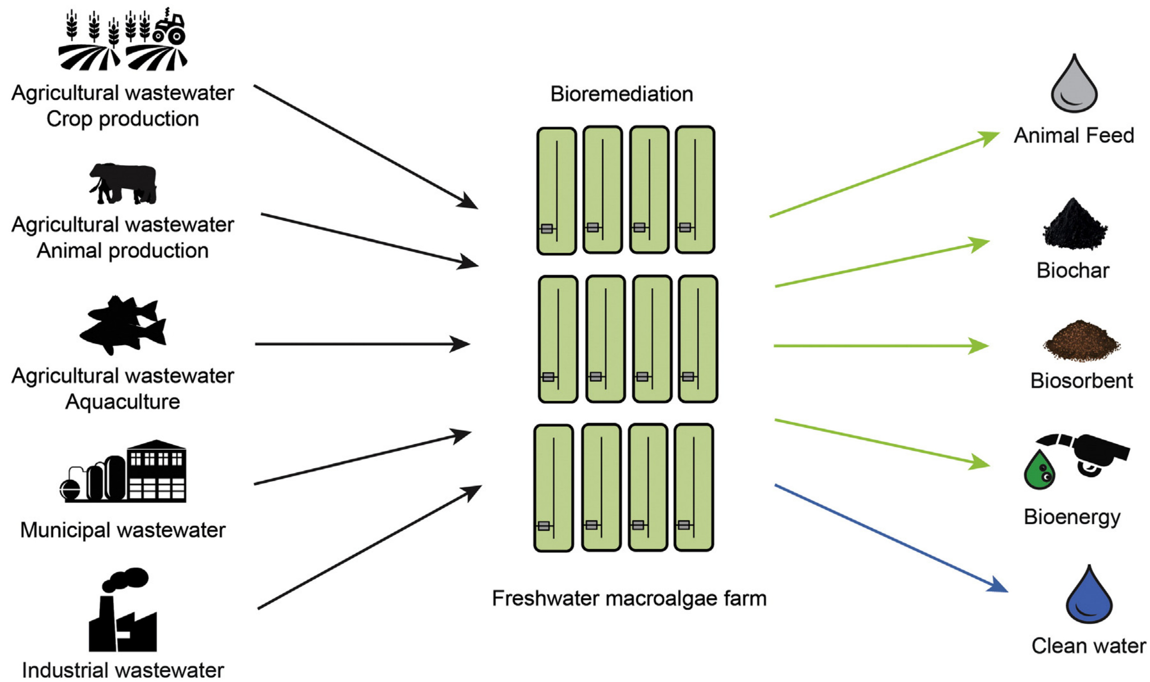

Fig. 1. Conceptual model of freshwater macroalgae integration in an industrial ecology system.

contaminated with heavy metals [14–17]. Additionally, it has broad environmental tolerances to temperature, nutrient concentration, salinity and water flow rate (Table 2), making it particularly suited to industrial scale cultivation where it can adapt to suit the local conditions without requiring industries to change operational protocols.

There are many benefits to cultivating freshwater macroalgae in wastewater. A primary benefit is that macroalgae can be produced without using large volumes of quality freshwater, thereby reducing competition between algal production and conventional agricultural production [18,19]. Moreover, when cultivated in nutrient-rich wastewater, for example from agriculture production or municipal water treatment, freshwater macroalgae do not require any additional fertiliser inputs [10,12,20,21] reducing input costs. Cultivation of freshwater macroalgae in wastewater can provide an alternative treatment service, removing nutrients, metals and other contaminants from the wastewater (see Section 3). This also recovers nutrients or minerals in the wastewater that would otherwise be lost by using macroalgal biomass grown in wastewater as a biomass resource (see Section 4). However, there are also considerations in cultivating freshwater macroalgae in wastewater. Macroalgal biomass cultivated in wastewater contaminated with heavy metals or other toxins may be unsuitable for some biomass applications such as human and animal food, or agricultural fertiliser [23]. Similarly, if the composition of wastewater varies considerably over time, then the biochemical composition of freshwater macroalgae cultivated in this water can vary, making it unsuitable for use in end product applications requiring algal biomass with a consistent biochemical composition. More generally the benefits and disadvantages of large scale algal cultivation of macroalgae require careful consideration, however, cultivation in wastewater alleviates some of the generic issues that have been raised in the broad scale production of microalgae, specifically contamination and harvesting [24].

3. Bioremediation

Freshwater macroalgae are highly successful at sequestering nutrients, metals and metalloids from wastewaters and in all cases the success of bioremediation is directly correlated to productivity, with increases in the growth of algae (productivity) resulting in increases in the bioremediation of contaminants [9,10,12,13,17,25,26]. As an example, for nutrient rich wastewater from agricultural production, a mixed algal species ATS system treating dairy manure had uptake rates of 0.40–1.26 g m^{-2} day^{-1} for nitrogen and 0.06–0.22 g m^{-2} day^{-1} for phosphorus across a range of productivities from 2.5–24 g DW m^{-2} day^{-1} [10]. When cultured on-site in wastewater from an intensive freshwater fish farm, *Oedogonium* had comparable uptake rates of up to 0.45–1.09 g m^{-2} day^{-1} for nitrogen and 0.08–0.13 g m^{-2} day^{-1} for phosphorus across a range of productivities from 3.8–23.8 g DW m^{-2} day^{-1} [12]. Similarly, when cultured in primary treated effluent from a municipal wastewater treatment facility, *Oedogonium* had stable uptake rates of up to 0.50 g m^{-2} day^{-1} for nitrogen and 0.11 g m^{-2} day^{-1} for

Table 1
Large scale cultivation of macroalgae in wastewater in Algal Turf Scrubber (ATS) systems and High Rate Algal Ponds (HRAP). System sizes are reported as length × width (m). Volume of water treated (volume) is reported as kL day^{-1}; only systems treating >20 kL water per day have been included. FW: freshwater.

Reference	Wastewater type	Type of algae used	System type	System size	Volume
[53]	Municipal, point source	FW macro- and microalgae	ATS	152 × 6.7	436–889
[10]	Dairy manure, point source	FW macro- and microalgae	ATS	30 × 1	134
[54]	Municipal, point source	FW macro- and microalgae	ATS	90 × 0.3	109
[52]	Municipal, point source	FW macro- and microalgae	ATS	90 × 0.3	112–1080
[55]	Agriculture, non-point source	FW macro- and microalgae	ATS	15.2 & 24.4 × 0.6	55
[51]	Agriculture, non-point source	FW macro- and microalgae	ATS	50 × 1	137
[8]	Agriculture, non-point source	FW macro- and microalgae	ATS	234 × 1.2	327
[56]	Municipal, point source	FW macroalgae	HRAP	22 × 11	36
[7]	Aquaculture, point source	Marine macroalgae	HRAP	10 × 1	36

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