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Integrating nutrient removal and solid management restricts the feasibility of algal biofuel generation via wastewater treatment

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ABSTRACT

While numerous studies have demonstrated the efficiency of secondary wastewater treatment (WWT) in high rate algae ponds (HRAPs), little consideration has been given to how the algal unit should be best integrated within a full treatment system complying with typical nutrient discharge standards. Using the case study of a 2000 person equivalent (P.E.), we first demonstrate that algal treatment is most efficiently used for combined carbon and nutrient removal because an HRAP designed for compliant N (or P) removal *de facto* provides free and environmentally-benign carbon removal. The large O_2 excess capacity for aerobic carbon removal also suggests primary suspended solid removal is unlikely needed, although grit removal remains necessary. We then demonstrate combining algal cultivation with anaerobic digestion is not economic at small scale because it offers marginal energy savings (e.g. 10.7€ P.E.$^{-1}$ yr^{-1}) while incurring significant costs for digestate transport offsite (e.g. 32.5€ P.E.$^{-1}$ y^{-1} at a distance of 50 km). Subsequent sensitivity analyses confirmed that while the potential of algae-to-biogas via WWT is limited (e.g. total cost of 38.2€ P.E.$^{-1}$ y^{-1} in our base case), integrating the use of HRAPs with solar drying has the potential to provide a more economical and energy-efficient WWT alternative for nutrient removal and recovery (24.4€ P.E.$^{-1}$ y^{-1}).

1. Introduction

Microalgae biotechnologies are broadly heralded as sustainable platforms for wastewater treatment (WWT) because microalgae provide additional capacities for oxygen supply, nutrient removal, and resource recovery [1,2]. Numerous studies have indeed demonstrated the efficiency of the 'algal unit' for treatment and/or resource recovery via biomass production and valorization (Tables S1–S3), where the algal unit is respectively used for simultaneous carbon and nutrient removal following solid removal during primary treatment (Configuration A, Fig. 1a); nutrient removal following carbon removal during secondary treatment (Configurations B and C, Fig. 1b and c); and nutrient removal from centrates following the anaerobic digestion (AD) of solids harvested during primary and/or secondary clarification ('centrate' refers to the liquid fraction of the digestate after centrifugation; Configuration D, Fig. 1d). However, little consideration has been given to how the algal unit should be best integrated within the full treatment system (e.g. which process configuration delivers the most cost-efficient treatment performance, Table S1), especially when considering biosolids management [3]. It is however critical to consider the full treatment system when designing and operating the algal unit due to potential synergetic or antagonist effects between individual treatment units (e.g. nutrient assimilation into biomass versus sludge management). For example, Steele et al. [3] noticed the importance of minimizing biosolids production during algal WWT due to the high projected costs of biosolid disposal and transport.

Based on a theoretical case study, the present research explores how HRAPs can be best integrated within a full treatment system capable of efficiently using land, energy and water while meeting stringent requirements for nutrient removal and biosolid management. Emphasis was given to nutrient removal for two reasons: First, it is especially relevant to algal WWT as WW is seen as a source of nutrients for algae cultivation in many 'algae to energy' projects [1,4]. Second, nutrients must be removed from wastewater prior discharge and the nutrients assimilated within biosolids must be safely disposed of, even following biosolid digestion. The latter is indeed seldom addressed in the literature, where it is often proposed that biosolids or their residues can be used as fertilizers without considering practical limitations [3,5]. The scope of this study was therefore reduced to cases where wastewater land irrigation is not possible due to economic, technical, or regulatory limitations, meaning that nutrients must be removed from the wastewater and disposed safely. As a general strategy, the main algal-based WWT system configurations discussed in the literature were first identified and classified based on the function of the algal unit (Fig. 1, Table S1). Two relevant sub-configurations where the algal-unit is used for

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Nomenclature

AD: anaerobic digestion
bCOD: biodegradable chemical oxygen demand (mg L^{-1})
bSS: biodegradable suspended solids (mg L^{-1})
C: carbon
COD: chemical oxygen demand (mg L^{-1})
EU: European Union
HRT: hydraulic retention time (d)
HRAP: high rate algal pond
N: nitrogen
P: phosphorus
PE: person equivalent
TN: total nitrogen (mg L^{-1})
TP: total phosphorus (mg L^{-1})
TSS: total suspended solids (mg L^{-1})
WW: wastewater
WWT: wastewater treatment
WWTP: wastewater treatment plant

complete biodegradable chemical oxygen demand (bCOD) and nitrogen (N) removal where then designed, modelled and compared.

Because algal-based WWT requires large areas of land [6] and wastewater transport over long distances is seldom practical [7,8], algal-based WWT will be most efficiently used for small to medium scale WWT [3, 9]. A 2000 person equivalent (P.E.) community currently treating WW using a low cost system (e.g. stabilization pond) was used as case study, a scenario representative of thousands of communities worldwide [10]. The 2000 P.E. capacity also represents the smallest WWT size above which nutrient (N, P) discharge is regulated in the European Union (EU) [11]. This threshold should not be regarded as a strict, universal, or static limit for the application of HRAPs, the focus being on cases where algal-based WWT is feasible but must comply with nutrient discharge standards. It should finally be noted that this study does not aim to design a 'perfect' universal algal-based WWT because each system must be specifically designed based on local constrains. Instead, and in the absence of knowledge on how to best integrate secondary algal-based wastewater treatment within a full wastewater treatment process, this study seeks to quantify, for the first time, the technological and economical challenges associated with biosolid management in order to identify critical areas for further research and process design optimization.

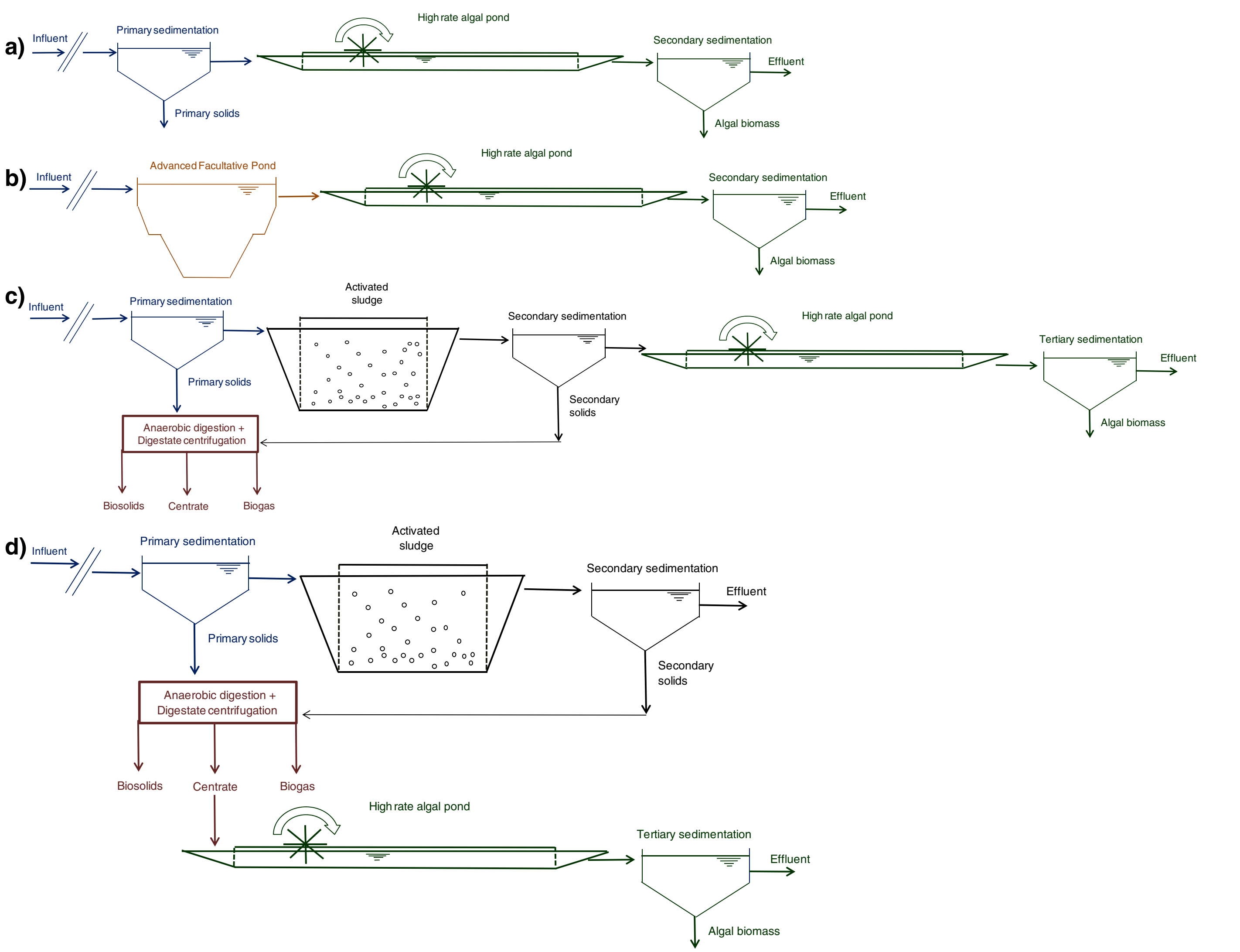

Fig. 1. Typical algae-based WWT configurations described in the literature: a) HRAP after primary sedimentation; b) HRAP after advanced facultative pond; c) HRAP after activated sludge processes; d) HRAP for centrate treatment.