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Environmental sustainability assessment of a microalgae raceway pond treating aquaculture wastewater: From up-scaling to system integration

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HIGHLIGHTS

- The LCA of pilot and up-scaled MaB-floc raceway ponds was conducted.
- Two valorisation pathways for MaB-flocs were compared.
- Up-scaling enhances the environmental sustainability of the system.
- Stirring has the largest environmental impact of the MaB-floc raceway pond.
- Valorizing MaB-flocs into shrimp feed is a preferable option over biogas.

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ABSTRACT

The environmental sustainability of aquaculture wastewater treatment by microalgal bacterial flocs (MaB-flocs) in an outdoor raceway pond was analyzed using life cycle assessment. Pikeperch aquaculture wastewater treated at pilot scale (Belgium; 28 m^2) and industrial scale (hypothetical up-scaling; 41 ponds of 245 m^2) were compared. The integration of the MaB-floc raceway pond in a broader aquaculture waste treatment system was studied, comparing the valorisation of MaB-flocs as shrimp feed and as biogas. Up-scaling improves the resource footprint of the plant (848 $MJ_{ex,CEENE}$ kg^{-1} MaB-floc TSS at pilot scale and 277 $MJ_{ex,CEENE}$ kg^{-1} MaB-floc TSS at industrial scale) as well as its carbon footprint and eutrophication potential. At industrial scale, the valorisation of MaB-flocs as shrimp feed is overall more sustainable than as biogas but improvements should be made to reduce the energy use of the MaB-floc raceway pond, especially by improving the energy-efficiency of the pond stirring system.

1. Introduction

From 2006 to 2011, the world aquaculture production increased by 34% (FAO, 2014), leading to an increasing production of nutrient-rich waste and wastewater that need to be treated. To enhance the sustainability of intensive aquaculture systems, recirculating aquaculture systems (RASs) which include a water treatment system have been developed. These RASs offer advantages in terms of reduced water consumption, and improved opportunities for waste management and nutrient recycling compared to conventional flow through aquaculture systems (Martins et al., 2010). In most RASs, effluent rich in nutrients and sludge, e.g. microscreen backwash water, is produced (Fig. 1). This backwash water needs further treatment before its discharge into surface waters. In line with the current paradigm shift towards resource recovery in wastewater technology, the sludge and the dissolved organic matter and nutrients in aquaculture backwash wastewater should be valorized. Because of increasingly strict regulations on discharged organic matter, the aquaculture sector is integrating fish sludge treatment in its core activities (Mirzoyan et al., 2010). Despite the presence of free ammonia, anaerobic digestion of fish sludge to produce biogas is a promising approach to reduce the environmental impacts of fish sludge treatment by recovering energy through biogas production while removing COD and BOD (Mirzoyan et al., 2010). The level of free ammonia in fish sludge

Abbreviations: BOD_5, biological oxygen demand; COD, chemical oxygen demand; TN, total nitrogen; TOC, total organic carbon; TP, total phosphorus; TSS, total suspended solids; VSS, volatile suspended solids.

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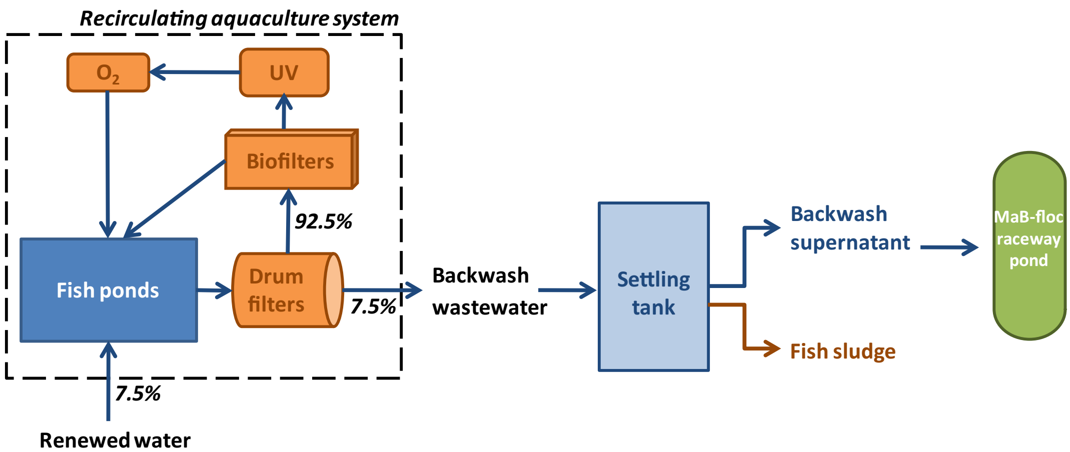

Fig. 1. Operation principle of the RAS raising pikeperch in Belgium (Aquaculture Practice Centre of Inagro, Roeselare, Belgium) releasing backwash supernatant treated in a MaB-floc raceway pond (Van Den Hende et al., 2014a).

can be inhibitory to anaerobic digestion but aquaculture effluents can be diluted (Mirzoyan et al., 2010) or mixed with another substrate (Nges et al., 2012) to enhance digester performance.

After removal of sludge from the wastewater, the remaining backwash supernatant needs further treatment, especially to remove dissolved organic matter and nutrients. To address the high costs of mechanical aeration in conventional activated sludge systems for treatment of backwash wastewater and to aim at a high nutrient recovery in microbial biomass, sunlight-based microalgal bacterial floc (MaB-floc, a bioflocculating consortium of bacteria and microalgae) technology was developed (Van Den Hende, 2014). In this system, costly mechanical aeration is replaced by photosynthetic aeration by the microalgae present in the MaB-flocs. In situ bioflocculation of MaB-flocs is obtained via operation as sequencing batch reactor (SBR). This enables the easy separation of MaB-flocs from the treated wastewater. Recently, promising results were obtained for the treatment of backwash supernatant of pikeperch (*Sander lucioperca* L.) aquaculture in a pilot-scale MaB-floc raceway pond in Belgium (Fig. 1), showing a possible production of 33 ton MaB-floc TSS $ha^{-1}\ y^{-1}$ (Van Den Hende et al., 2014a).

As MaB-flocs grow, they need to be harvested from the ponds and the harvested MaB-flocs need further valorisation. A possible pathway is the use as feedstock for anaerobic digestion to produce biogas. Anaerobic digestion of wastewater treatment by-products and of wastewater-grown algae has been shown to be a valuable pathway (Collet et al., 2011). Nevertheless, the anaerobic digestion conversion efficiency of MaB-flocs grown on pikeperch backwash supernatant is below 40% (Van Den Hende et al., 2014c); a common problem in anaerobic digestion of several microalgal species (Ward et al., 2014). This is also a low-value valorisation pathway, in the order of 30–60 € per ton MaB-floc VSS (Van Den Hende, 2014).

An alternative MaB-floc valorisation pathway is using MaB-flocs as pigment-enhancing feed for herbivorous aquaculture species. Recently, it was shown that dried MaB-flocs can replace 8% of the ingredients (mainly wheat) of diets of Pacific white shrimp *Litopenaeus vannamei* (Boone, 1931) while enhancing their pigmentation (Van Den Hende et al., 2014b).

Switching from linear fish aquaculture and separated aquaculture sludge and wastewater treatment to an integrated MaB-floc-based aquaculture waste treatment system could be a key strategy to mitigate the environmental footprint of the aquaculture sector; e.g. by valorizing fish sludge into biogas and recovering nutrients through MaB-floc cultivation. In the context of actual resource depletion and climate change, not only the technical potential but also the environmental sustainability of such a system needs to be known before implementing it on industrial scale. Some studies analyzing the environmental sustainability of wastewater-based algal biofuels (Mu et al., 2014; Sander and Murthy, 2010) and biogas (Collet et al., 2011) have been performed but the environmental sustainability of alternatives to such energy carriers has not been studied in the case of aquaculture wastewater-based microalgae production. Life cycle assessment (LCA) is a recognized methodology to assess the environmental burdens of a system. This methodology follows the framework of International Standards Organization (ISO) 14040 and 14044 (ISO, 2006a,b) and allows comparing the environmental impact of different steps of a studied process, identifying the steps which could be improved and avoiding environmental impact shifting from one step to another. In the previously cited studies, LCA has shown to be a useful instrument to highlight the improvement potential of microalgae cultivation systems. Thus, this study aims to answer the two following questions: (1) how can the environmental impact of a MaB-floc SBR system treating pikeperch culture wastewater be improved? (2) how should MaB-floc technology be implemented in an integrated aquaculture waste treatment system to enhance its environmental performance?

To assess the environmental efficiency of an integrated MaB-floc system, this study first evaluates the environmental sustainability of a pilot MaB-floc SBR raceway pond treating backwash supernatant from a pikeperch RAS in Belgium (Van Den Hende et al., 2014a). The environmental impact based on a LCA of this pilot plant was evaluated. The pilot plant was then compared to an up-scaled plant modeled as a linear projection of the pilot plant (called linearly up-scaled plant) and to three improved up-scaled plants in which some parameters were modified. To determine the potential of impact reduction associated with system integration, the improved plants were implemented into two industrial scale scenarios in which MaB-flocs were valorized into biogas or into shrimp feed. These two scenarios were compared to the baseline scenario, in which aquaculture backwash supernatant is released in the sewage system without any treatment by MaB-flocs.

2. Methods

2.1. Description of the MaB-floc-based raceway ponds

2.1.1. Backwash supernatant characteristics

The analyzed pilot plant treated real aquaculture backwash supernatant produced by the pikeperch RAS of the Aquaculture