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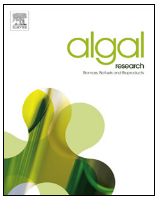

Valorisation of aquaculture effluents with microalgae: The Integrated Multi-Trophic Aquaculture concept

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ABSTRACT

One of the main problems of aquaculture is the environmental impact of its effluents, which are rich in particulate and dissolved nutrients from undigested feed and faeces. In intensive aquaculture systems the main dissolved nutrient present in effluents is ammonium, which is converted into nitrate through nitrification in aerobic bacterial filters. Microalgae can substitute bacteria by efficiently harvesting and recycling nutrients. The main advantage of the use of microalgae is the obtainment of biomass that can be valorised by using it as feed for other aquatic organisms in a process known as Integrated Multi-Trophic Aquaculture (IMTA). Cultured microalgae can be used to feed low trophic level fish, herbivorous fish and molluscs, which can in turn be sold on the market, as well as being a source of valuable chemicals. Nevertheless, most IMTA studies have been focused on the use of macroalgal biofiltration. The incorporation of microalgal culture with controlled cultivation conditions as biofilters in land-based IMTA systems presents high potential because they achieve more efficient photosynthetic rates and higher growth rates and present better biochemical composition than macroalgae. The present review comprises information on the microalgal-based IMTA systems described so far in the literature. Additionally, microalgae culture methods that are applied to aquaculture wastewater treatment, such as periphyton, microalgal-bacterial consortiums and cell immobilization are assessed.

1. Introduction

Aquaculture has experienced a rapid development throughout the world, becoming in recent years the main contributor to the fisheries sector. In 2012, fish aquaculture production more than doubled in comparison to the production in the year 2000, reaching 67 million tons [1]. One of the main problems derived from intensive aquaculture is the environmental impact of the effluents rich in particulate organic matter and dissolved nutrients from undigested feed and faeces that may drive the eutrophication process in receiving waters [2]. Eutrophication resulting from waste from land or open-water aquaculture results in the senescence and disintegration of phytoplankton blooms, which leads to low dissolved oxygen in receiving waters [3,4]. This process is especially harmful in the case of terrestrial aquaculture, in which contaminants can accumulate in one restricted area. In this case, farm discharges threaten habitat's health [5]. The most pollutant effluents derive from fish intensive aquaculture, in which great amounts of protein-rich feed are required to sustain highly dense cultures of carnivorous fish. This is due to the high protein content (65% to 75%) of fish body [6], that requires three times more protein than humans, and to its low digesting efficiency which generates five times more waste than the human metabolism [7].

Ammonium (NH_4^+) from protein metabolism is the main nutrient in aquaculture effluents [8]. Generally, in intensive aquaculture systems, solids are removed by sedimentation or sieving, and ammonium is mostly converted into nitrate (NO_3), through nitrification in aerobic bacterial filters [9] (Fig. 1). Therefore, current effluent treatment technology relies on expensive bacterial systems [10] and does not add any value to the process beyond the removal of the contaminating nutrients from the effluent. Nitrifying bacteria used in these systems are primarily obligate autotrophs, which consume carbon dioxide as their primary carbon source, and obligate aerobes with high requirements of oxygen to grow [9]. In some cases, the aerobic treatment is followed by anaerobic treatment in order to favor denitrification of the produced nitrate (Fig. 1). The direct bacterial anaerobic conversion of ammonium to N_2 and biomass (ANAMMOX) consist of delicate and expensive treatment systems which are not suitable for implementation in aquaculture effluents [11]. Alternatively, photoautotrophic algae-based treatment systems can be used, having been successfully implemented [12,13], allowing in some cases a single-step treatment of effluents, with the production of biomass that can be valorised through different applications.

Oswald & Golueke [14] first proposed algal photosynthesis as a sustainable process for waste water treatment. Macroalgae are the typical algal biofilters used in aquaculture systems [15]. As reviewed by Chopin et al. [2], the integration of seaweeds with fish cultures has been studied in open-water system conditions in Canada, Japan, Chile, United States

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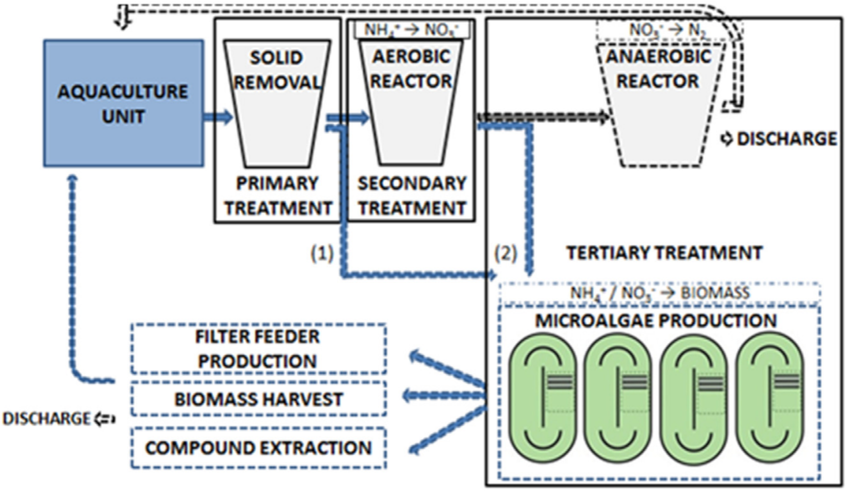

Fig. 1. Schematization of proposed microalgal-based IMTA system for LBAS and RAS, comprising microalgal biofiltration, filter feeder production, biomass harvest and compound extraction. Blue solid lines represent water flow; blue discontinuous lines stand for microalgae treatment pathways (1 – after solid removal; 2 – after nitrification); black discontinuous lines mean substituted pathways. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and in Norway, in the 1990s. Macroalgal biofiltration in land-based systems, that relate more closely to the microalgae-based systems reviewed in this work, were studied in the United States for the first time in the 70s and in Israel in the 80s. Further studies were carried out in Spain, Sweden, and Chile, in the 90s. Even though the use of microalgae as biofilters in aquaculture is not as prevalent as macroalgae, they can be used for the efficient harvest and recycling of nutrients present in aquaculture effluents, since they efficiently treat wastewater, lowering chemical oxygen demand (COD) and biological oxygen demand (BOD) and remove nutrients and heavy metals [16]. Microalgae have antibacterial and probiotic action, thus inhibiting the proliferation of pathogens [17]. Furthermore, microalgae have higher photosynthetic efficiency and higher nitrogen uptake rates, independently of substrate concentration and form (ammonium or nitrate) due to its higher relative surface area [18]. Analogous dynamics are observed for other nutrients, like phosphorus, which is present in aquaculture effluents causing eutrophication processes [19]. Moreover, microalgal treated effluents generate high value biomass presenting better biochemical composition that can be valorised into premium feed for animals, being suitable for direct ingestion of herbivorous fish, shrimp and molluscs, as it has been successfully observed for clams and oysters [12]. Furthermore, microalgal biomass constitutes a source of high value products, e.g. fatty-acids, pigments, polysaccharides, etc. [20,21].

The use of macro and microalgae for the treatment of aquaculture effluents and the subsequent use of the obtained biomass for feeding other aquatic organisms is a process known as Integrated Multi-Trophic Aquaculture (IMTA). The main purpose of IMTA systems is increasing long-term sustainability and profitability of aquaculture, as the wastes of one crop (fed animals) are converted into particulate matter – macro and microalgae – that can be used to feed low trophic level animals that can in turn be sold on the market [22,23]. Further enhancement of the economic strength of IMTA systems, can be achieved through the extraction of high value compounds from algal biomass. This strategy constitutes an excellent example of microalgal-based circular economy in which the diversification of the produced species increases the resilience of the economic activity to market instabilities and occasional loss of crops, closing the loop of product lifecycles by recycling and re-using resources and consequently benefiting environment and economy [13]. Additionally, natural stocks depletion, which is aquaculture's biggest environmental problem, can be attenuated by using microalgae to feed low trophic level animals in IMTA, through the diversification of produced species by including non feed-dependent animals, like bivalve molluscs [22].

The basal concept of IMTA has been applied throughout human history. In China, microalgae have been used for millennia in integrated systems, alongside with macroalgae and cyanobacteria. In such systems, rice is cultured with fish and algae [24], potentially increasing production by 8 to 47% [25]. Aquatic weeds and phytoplankton, which naturally exist in this environment, absorb dissolved nutrients and are then consumed by fish, turning this process into a polyculture system, rather than a monoculture. The polyculture system allows the effective usage of nutrients in water, by converting nutrients, in weeds and phytoplankton, into soluble forms, through fish alimentation and digestion, which are again available for the rice culture. The same basic concept is applied nowadays to intensive IMTA systems.

Regarding IMTA, current research and development on water treatment is largely devoted to macroalgae. The seaweed genera most common in mariculture biofiltration are *Ulva* and *Gracilaria*, which treat effluent water converting it into a clean and oxygen-rich effluent that can therefore be readily recirculated back to the fish ponds or discharged [24]. Even though the first conceptualization [26] of a "modern" integrated aquaculture system comprised the use of controlled microalgae blooms as biofilter and feed, microalgal-based effluent treatment in IMTA systems have since been largely neglected [15,27]. Since microalgae can simultaneously play the role of biofilters, oxygenizers and feed, dense microalgal populations are excellent candidates for being integrated in IMTA systems [28], either in an extensive or intensive fashion. Microalgae cultivation can be developed in fishponds and their effluents, providing in situ bioremediation [28–30]. Biofiltration with microalgae of extensive and intensive aquaculture effluents can also take place in separate culture units. In this case, the use of microalgae can either be faced as an uncontrolled agent in effluents [31–33], or as intensive cultivation units in which culture conditions have to be carefully designed in order to enhance yield and treatment efficiency [34,35]. Microalgal biofiltration is a way of producing high-value biomass as a low-cost commodity, valorising otherwise lost resources.

Filtering animals, like molluscs, diversify production and serve a fundamental role in IMTA systems by decreasing particulate organic matter, mainly microalgae, in the water column, as demonstrated by the co-culture of salmon with mussels or oysters that successfully reduced nutrient pollution from waste salmon feed [24]. Indeed, special attention could be given to bivalve molluscs as they feed on microalgae in all growth stages (e.g. oysters, scallops, clams and mussels) [36]. Bivalves reduce suspended particulates, including organic and inorganic particles, phytoplankton and bacteria [37], reducing water turbidity by

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