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Multitrophic integration of the tropical red seaweed *Solieria filiformis* with sea cucumbers and fish

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ABSTRACT

Integrated multi-trophic aquaculture systems can be very complicated as they involve interactions between different fed and extractive organisms, where each organism can have different peaks of nutrient production or absorption and assimilation during the day. Integrated seaweeds must be able to absorb nutrients under a wide range of conditions, making seaweed selection and the effects of its integration a high importance subject, particularly for tropical, poorly studied species. This study evaluated ammonium and phosphate absorption in light and dark conditions and their biochemical implications using *Solieria filiformis*, a promising tropical seaweed species, and its performance when integrated with fish and sea cucumbers. Nutrient pulses were added under laboratory conditions, and integration was evaluated through a cascade design in a recirculation aquaculture system (RAS), including fish and sea cucumber with tanks connected through their effluents. *S. filiformis* had high absorption rates under light and dark conditions either in single or combined pulses during the day. In general, controls without nutrient additions showed lower growth rates, lower Chl *a*, and a constant decrease in phycoerythrin, but light, dark, or combined nutrient pulses did not differ. In the integration experiments, seaweeds without enriched nutrient effluent had significantly lower growth rates, fewer ramifications, and were brittle. Flexibility improved with the integration of sea cucumbers, and, with fish, branches were thinner and more abundant. *S. filiformis* has been proven as an effective species to be considered for integration with fish and sea cucumbers in tropical environments.

1. Introduction

Aquaculture has been growing steadily in the past decades, thus gaining importance to supply the demand for fish and other aquatic organisms (FAO, 2018). Site availability, water quality, the ecological loading capacity of the sites, and feed quality are among some of the limitations that aquaculture expansion must face in the future (Troell et al., 2009). Environmental impacts from this practice are also on the rise, making it necessary to use sustainable aquaculture practices that prioritize the environment (Chopin et al., 2008).

In this regard, several authors have proposed an integrated approach with multitrophic aquaculture to solve these constraints. Integrated multitrophic aquaculture (IMTA) is based on the addition of extractive organisms (i.e., seaweeds or oysters) that take advantage of the excretions from superior trophic levels (i.e., fish and crustaceans) that transform the excess of nutrients into new biomass (Chopin et al., 2001; Troell et al., 2003; Neori et al., 2004).

Complexity and diversification of IMTA systems have been recently discussed by several authors highlighting needs and challenges (Martínez-Espiñeira et al., 2015; Park et al., 2018; Kleitou et al., 2018; Knowler et al., 2020). In many cases, management of the systems (recirculating or flow through rates, water residence times) and the feeding behavior and nutrient excretion of the organisms involved (diurnal or nocturnal) will influence the successful integration of extractive organisms. For example, sea cucumbers, one of the most promising IMTA detritivores, are mainly nocturnal (Cubillo et al., 2016; Zamora et al., 2018; Zamora and Jeffs, 2012, 2011), while most cultivated fish species are diurnal, or their feeding occurs at daytime (Boujard and Leatherland, 1992). These circumstances may influence nutrient excretion and the times when nutrient peaks occur, which is observed regularly within one or two hours after feeding (Porter et al., 1987; Rosas et al., 1999; Yang et al., 2006).

In general nutrient absorption by macroalgae requires fewer resources when light is present, as the energy needed for nutrient uptake comes directly from the photosynthetic process, and some nutrients enter the cells with CO_2 (Huppe and Turpin, 1994; Harrison and Hurd, 2001). Nutrient uptake rates for some species of seaweeds show that red and brown algae display a reduction of about a third to half of the

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