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Constructed wetland with *Salicornia* as a biofilter for mariculture effluents

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A B S T R A C T

The performance of a constructed wetland (CW) with *Salicornia persica* (*Chenopodiaceae*) as a biofilter for effluent water drained from a semi-open recirculating mariculture system was studied in southern Israel. The results demonstrate the effectiveness of N, P and total suspended solid (TSS) removal from mariculture effluent by a CW operating with this plant. The CW was exposed to high (3.3 ± 0.26 g N m^{-2} d^{-1}) and low (0.13 ± 0.02 g N m^{-2} d^{-1}) nutrient loads (NL) in two hydraulic regimes, surface flow (SF) and subsurface flow (SSF). In addition to the CW being studied as marine fishpond effluent water purifier, the *Salicornia* yield was evaluated as a marketable agricultural by-product. Eight CW ponds were covered under a 750 m^2 greenhouse. The surface area of each CW pond was 24.3 m^2 (13.5 m length, 1.8 m width and 0.30 m average depth) and volume of 7.3 m^3. The fishponds' effluent drained in a continuous mode into one end of each CW pond and out from the opposite end (plug flow) at a hydraulic load (HL) of 0.5 m^3 h^{-1}, a hydraulic loading rate (HLR) of 0.49 m d^{-1}, and a hydraulic retention time (HRT) of 1.51 d^{-1}. Dissimilation processes such as ammonification, nitrification and denitrification with assimilation by the plants performed as in natural wetlands. *Salicornia* wet yield was 23 ± 1.6 and 26 ± 4.6 kg m^{-2} y^{-1} in the SF and SSF flow regimes, respectively, at the low nitrogen load, and 20.1 ± 2.4 and 17.4 ± 3.1 kg m^{-2} y^{-1} in the SF and SSF flow regimes, respectively, at the high nutrient load. Total nitrogen (TN) uptake by *Salicornia* tissue itself excluding the wetland activity (including roots) was 29.1 ± 3.3 and 26.9 ± 3.1 g N m^{-2} y^{-1} in the SF and SSF flows, respectively, at low nitrogen load, and 18.5 ± 3.5 and 13.3 ± 3.3 g N m^{-2} y^{-1} at high N loads in the SF and SSF flow regimes, respectively. The contribution of *Salicornia* as a nitrogen biofilter at high NL was negligible (0.5%–0.9% of the total dissolved nitrogen [TDN]) compared to the low NL (56%–61.4% of the TDN) in both SF and SSF regimes respectively. Our results show that the SF regime with *Salicornia* would likely be more efficient in facilities with low NL (e.g., fish hatcheries), whereas the SSF regimes would be more efficient with high NL (e.g., super-intensive fish farms). Using CW systems for effluent treatment requires a relatively extensive area. According to our results, about 10,000 m^2 of CW with *Salicornia* are required to remove nitrogen and TSS produced from 900 kg of 45% crude protein fish feed (11 m^2 kg^{-1} of feed) during one year. The income generated from selling the *Salicornia* as an agricultural crop, together with savings on water treatment and potential fines, contributes to the system's economical viability.

1. Introduction

Natural wetlands are an important component of marine and freshwater ecosystems. They hold and recycle nutrients, provide habitat, breeding and nursery grounds for many wildlife species, and control and buffer natural floods (Hammer and Bastian, 1989). In addition, wetlands can efficiently remove organic matter, suspended solids and nutrients (N, C, P) through various processes, including filtration, sedimentation, biological and microbiological absorption, and assimilation (Hammer and Bastian, 1989). The environmental and economical significance of wetlands has been pointed out by several authors (Kadlec and Knight, 1996; Lin et al., 2005; Sindilariu et al., 2008, 2009b).

The use of man-made constructed wetlands (CW) as biofilters is a relatively new technology. The construction of wetlands to provide habitat to a variety of organisms and improve water quality began in the 1970s (Kadlec and Knight, 1996). CWs were set up to provide flood control (flood control wetlands), to compensate for and help offset the decline of natural wetlands resulting from agriculture and urban development (habitat wetlands), to improve water quality (treatment wetlands), and to be used for production of food (aquaculture wetlands).

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Constructed wetlands utilizing higher plants have also been used to treat aquaculture effluent (Mitsch and Gosselink, 2000; Rousseau et al., 2004; Schwartz and Boyd, 1995).

Major physical, chemical and biological processes in CWs are: transport of total suspended solids (TSS), nutrient cycling, biomass production, nutrient uptake by plants and animals, and distribution of organic matter and oxygen. The major parameters to be taken into consideration for the design of a CW are: surface and cross section area, nutrient load (NL), hydraulic load (HL), hydraulic retention time (HRT) and hydraulic loading rate (HLR) (Kadlec and Knight, 1996). Two basic flow regimes were devised for CWs: free surface flow (SF) and subsurface flow (SSF) (Kadlec and Knight, 1996; Schulz et al., 2003).

CWs have been exploited for rearing crayfish, shrimp, and commercial fish species in shallow ponds and used mainly for treatment of freshwater aquaculture effluent (Brown et al., 1999; Buhmann and Papenbrock, 2013; Lin et al., 2002a,b, 2003; Schulz et al., 2003; Schwartz and Boyd, 1995; Tilley et al., 2002). If relatively inexpensive land is available, CW for aquaculture can be cost effective since they require only moderate capital investment, with low energy consumption and low maintenance expenses (Lin et al., 2005; Sindilariu et al., 2009a,b).

Only recently has the concept of applying CW to mariculture systems been studied (Lymbery et al., 2006; Sansanayuth et al., 1996; Webb et al., 2012), and the use of both CW types, using *Salicornia* as biofilter for marine fishpond effluent, is a new approach (Webb et al., 2012).

Protein is the most expensive component in marine organism feed and the main source of nitrogenous pollution in aquaculture. In conventional mariculture, fish assimilate only 25–30% of the nitrogen and phosphate in their diets (Lupatsch and Kissel, 1998), while the rest is excreted into the water, mainly as dissolved inorganic or solid organic compounds. The effluent, rich in this organic matter, may harm coastal ecosystems and should be treated before being discharged into the sea. Water can be treated biologically, using bacteria (nitrification and denitrification processes) (Van Rijn, 1996), macroalgae, or microalgae (Neori et al., 2004; Shpigel and Neori, 1996). Higher plants can be yet another solution for the assimilation (removal) of dissolved nutrients, suspended solids, and reduction of biological oxygen demand (BOD) and pathogens from land-based aquaculture systems (Buhmann and Papenbrock, 2013; Lin et al., 2003; Schwartz and Boyd, 1995; Sindilariu et al., 2008; Webb et al., 2012; Zhang et al., 2011). Halophytes are naturally salt tolerant plants and therefore have found application in agro-engineering projects such as recycling of agricultural and industrial brines (Jordan et al., 2009), revegetation of salt-affected tidal zones (Ruan et al., 2008), urban landscaping irrigated with saline water sources (Glenn et al., 2009), treatment of aquaculture effluent (Brown et al., 1999), and phyto-remediation of contaminated soils (Lin and Mendelssohn, 2009; McKeon et al., 2005). Studies on biofiltration of aquaculture effluent by various halophyte plants have been reviewed recently by Buhmann and Papenbrock (2013).

Dominant plant species in natural temperate marine wetlands are the salt marsh halophytes known as pickelweed (*Salicornia* spp.) (Davy et al., 2001). *Salicornia bigelovii* has been used in restoration projects throughout the world, showing an efficient nutrient removal capacity, even at full seawater salinity (Brown and Glenn, 1999). In addition, *Salicornia* spp. possesses a commercial value. The high mineral content, vitamins, antioxidant compounds and polyunsaturated fatty acids in the shoots make *Salicornia* a healthy food vegetable for human consumption (Ventura et al., 2011). The high oil content in the seeds, particularly rich in polyunsaturated fatty acids, also makes *Salicornia* a promising oilseed crop which could be used as a feed supplement for ruminants in arid regions (Glenn et al., 1991, 1994, 1997; Miyamoto et al., 1996; Swingle et al., 1996). The dwindling supply of freshwater throughout the world makes mariculture and use of saline water for crop irrigation an ever more valuable alternative to freshwater use. The aim of this study was to evaluate the performance of a CW with *Salicornia* as a biofilter for mariculture effluent and the potential of *Salicornia* as an edible by-product.

2. Materials and methods

The experimental work was carried out in a pilot CW system in Eilat (Red Sea, Israel) from November 2008 to April 2009. A comparison of the performance of CWs was made by exposing the systems to high and low dissolved nutrient loads from a recirculation aquaculture system (RAS), using two water flow regimes: surface flow (SF) and subsurface flow (SSF), with the cultivation of *Salicornia persica* as an edible by-product. Seeds of *Salicornia* were sown directly in containers filled with perlite (Agrekal Habonim Industries Ltd., 2000. Moshav Habonim, Israel; www.agrekal.co.il) and irrigated with 50% diluted seawater (20 ppt salinity) in a separate nursery. After germination, the seedlings were gradually exposed to increasing salinity up to full strength seawater over a three week period. The containers were then transferred to the CW.

2.1. Constructed wetland

The CW systems had been established two years before the beginning of the experiments. No further acclimation was made. Eight CW ponds were protected by a 750 m^2 greenhouse (Fig. 1). The surface area of each CW was 24.3 m^2 (13.5 m length, 1.8 m width and 0.30 cm average depth) with a volume of 7.29 m^3, for a total area of 194.4 m^2. The bottom of the CW was lined with PVC sheets and covered with a 30 cm thick layer of sand. The CW ponds were then coated with layers of gravel of various size gradients (1–8 cm), reducing the actual water depth to 0.3 m. The CW design is outlined in Fig. 2. Effluent drained horizontally into one end of each CW pond and out from the opposite end. A vertical overflow standpipe maintained the water at the desired level. Effluent drained continuously into the CW at a hydraulic load (HL) of 0.5 $m^3\ h^{-1}$ for each CW pond. Hydraulic loading rate (HLR — HL / surface area) was 0.49 m d^{-1}, and hydraulic retention time (HRT — HL × 24 / volume) was 1.51 d^{-1}. Nutrient composition and concentrations (low and high nutrient load (NL)) of the incoming effluent water are summarized in Table 1.

2.2. Experimental design

Two hydraulic flow regimes were evaluated: surface flow (SF), with the water circulating above the substrate, and sub-surface flow (SSF), with the water circulating through a gravel and stone substrate (Schulz et al., 2003), in the presence and absence (control) of *Salicornia* plants. Three CW ponds with *Salicornia* were exposed to SF and three to SSF flow regimes. Two additional CW ponds without *Salicornia*, one SF and one SSF flow regime, served as controls to be assessed qualitatively. The CW ponds were exposed to low and high nutrient loads (NL) from effluent of a 1000 m^3 commercial, super-intensive, semi-recirculated aquaculture system (ARDAG Ltd., Eilat) growing 100 tons of gilt-head sea bream (*Sparus aurata*) ranging 1–500 g in size. The fish were fed with a feed containing 45% protein at a rate of 2% body weight d^{-1}. The experiments with low NL were carried out from November 2008 to January 2009, and the experiments with high NL were carried out from January 2009 to April 2009, i.e., 90 d for each set of experiments. A 16-hour light regime was maintained throughout the experiments using artificial light after sunset to prevent inflorescence of the *Salicornia* plants (Ventura et al., 2011b). Abiotic parameters (temperature, pH, oxygen) and flow rates were measured daily at 08:00 and at 14:00. Yield and growth rates were measured monthly. Biochemical composition of the *Salicornia* was determined twice in December for the low NL and twice in March for the high NL at a two-week interval. Nutrient dynamics (ammonia, nitrate, nitrite, phosphate, TSS) and nitrogen budget of the CW were measured during four 24-hour observations at 6 h