Ecological Engineering 61 (2013) 145–153

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

The effect of halophyte planting density on the efficiency of constructed wetlands for the treatment of wastewater from marine aquaculture

J.M. Webb[a,*], R. Quintã[a], S. Papadimitriou[b], L. Norman[b], M. Rigby[c], D.N. Thomas[b,d,e], L. Le Vay[a]

[a] Centre for Applied Marine Sciences, College of Natural Sciences, Bangor University, Wales LL59 5AB, UK
[b] School of Ocean Sciences, College of Natural Sciences, Bangor University, Wales LL59 5AB, UK
[c] Llyn Aquaculture Ltd., Afonwen Farm, Chwilog, Pwllheli, Gwynedd, Wales LL53 6TX, UK
[d] Finnish Environment Institute (SYKE), Helsinki, Finland
[e] Arctic Research Centre (ARC), Aarhus University, Aarhus, Denmark

ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form 23 July 2013
Accepted 20 September 2013
Available online 20 October 2013

Keywords:
Salicornia
Constructed wetland
Aquaculture
Waste water
Halophyte
Nutrient removal

ABSTRACT

The low volume batches of highly-concentrated wastewater discharged from land-based marine recirculating aquaculture systems are ideally suited for treatment by halophyte planted constructed wetlands. To evaluate the role of plants and the effect of planting density on yield and performance in small-scale saline constructed wetlands (CWs), $NH_4^+ + NO_3^- + NO_2^-$ = total dissolved inorganic nitrogen (TDIN) and dissolved inorganic phosphorus (DIP) were measured at regular intervals over 24 h periods. CWs were planted with the halophyte *Salicornia europaea* at high- and low-densities and were compared to the performance of unplanted controls. *S. europaea* plants were cropped regularly to assess potential commercial yield at the two densities. There was no significant effect of planting density on performance or crop yields and planted beds consistently outperformed the control beds removing 62.0 ± 34.6 mmol N m^{-2} d^{-1} (34–73% of influent TDIN) compared to 23.0 ± 26.8 mmol N m^{-2} d^{-1} (−1% to 41% of influent TDIN) by control beds. Results for DIP were less clear, significant removal occurred only once, with reduction of 18.3 ± 5.0 mmol P m^{-2} d^{-1} by planted beds and 18.1 ± 2.6 mmol P m^{-2} d^{-1} by the unplanted controls. The results demonstrate the effectiveness of halophyte-planted CW in treatment of marine aquaculture wastewater.

1. Introduction

Aquaculture production currently contributes almost half of all global fish production (60 million MT), and is expected to increase by a further 60–100% over the coming decades (FAO, 2010). The development of marine aquaculture, particularly of fish and crustaceans, has largely focused on the intensive production of carnivorous or omnivorous species in coastal cages and ponds. The intensification of production in land-based intensive marine recirculating aquaculture systems (RAS) is a relatively recent development and offers the potential for bio-secure, environmentally-contained production (McCarthy and Gardner, 2003; Park et al., 2008; Tal et al., 2009). This represents a step away from more traditional ‘flow through’ or ‘open systems’ that can discharge high volumes of wastewater to the environment, which are difficult to remediate (Folke and Kautsky, 1992). In contrast, recirculating aquaculture systems produce relatively small batches of highly concentrated effluents that are more amenable to treatment prior to discharge (Piedrahita, 2003), and that may be suitable for treatment in constructed saline wetlands.

Constructed wetlands (CW) are increasingly applied for the treatment of numerous types of effluent from agriculture, heavy industry, municipal and intensive freshwater land-based aquaculture (Vymazal, 2005a,b). There has been considerable research into optimal wetland design, plant assemblages and sediment types (Tanner, 1994, 1996; Tanner et al., 2012; Vymazal, 1996, 2002, 2005a,b; Lin et al., 2002a–c, 2005; Schulz et al., 2003; Haddad et al., 2006), however, much of this work has been into systems planted with glycophyte plant species for remediation of freshwater effluents which is not directly transferable to saline systems. There is growing interest into the potential of constructed wetlands planted with facultative or obligate halophytes for the remediation of saline effluent and marine intensive land-based aquaculture wastewaters (Brown et al., 1999; Lin et al., 2002a,b, 2003, 2005; Lymbery et al.,

---

* Corresponding author at: Tel.: +44 1248 388805.
E-mail address: j.webb@bangor.ac.uk (J.M. Webb).

0925-8574/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecoleng.2013.09.058

2006, 2013; Sousa et al., 2011; Calheiros et al., 2012; Webb et al., 2012).

Since plant roots are the major source of oxygen in subsurface flow (SSF) wetlands, aside from atmospheric diffusion (Brix, 1994) the role of higher plants is crucial in establishing a successful CW. Plants in CWs not only increase microbial assemblages in the root zone, release oxygen into the sediment and assimilate nutrients, but they also maintain the hydraulic conductivity of the substrate (Brix, 1994; Haberl et al., 1995). Additionally they can provide a commercial crop that can result in above-ground biomass being almost completely removed from the system (Webb et al., 2012). Reported nitrogen uptake by macrophytes in CWs varies greatly, but is generally in the range of 10–30% of influent concentrations (Koottatep and Polprasert, 1997; Burgoon et al., 1991; Haddad et al., 2006; Lin et al., 2002c; Brown et al., 1999). However, much higher values have been reported with direct plant uptake of nitrogen reaching 85–100% of influent total dissolved inorganic nitrogen (TDIN) (Rogers et al., 1991 as cited in Hunter et al., 2001; Romero et al., 1999; Webb et al., 2012).

Previous research into CWs planted with emergent macrophytes (e.g. *Phragmites* spp., *Typha* spp.) for treatment of saline/brackish wastewater is limited (Lin et al., 2002a,b; 2003; 2005; Lymbery et al., 2006; Klomjek & Nitisoravut, 2005), and there are even fewer studies of the use of halophyte planted CWs for saline wastewater remediation (Brown et al., 1999; Brown & Glenn, 1999; Sousa et al., 2011; Calheiros et al., 2012). The present study and a previous work (Webb et al., 2012) report findings from a 3 year investigation evaluating the potential of constructed wetlands planted with the halophyte *Salicornia europaea* agg. (L) for use as a biofilter for wastewater discharged from a commercial pilot RAS unit growing marine shrimp (*Litopenaeus vannamei*) at high stocking densities. Recent results with *S. europaea* indicate that high levels of nutrient removal can be achieved (Webb et al., 2012) and the present study is a more detailed investigation into rates of removal over daily treatment cycles, CW effectiveness under previously simulated high nutrient loading and the role of the halophyte *S. europaea* in the CW system.

The objectives were to:

1. Investigate the effects of planting density on removal rate of TDIN and dissolved inorganic phosphate (DIP).
2. Evaluate the effect of planting with *S. europaea* agg. (L) through comparison of overall uptake and removal rates of TDIN and DIP to unplanted control CWs.

2. Materials and methods

2.1. Filter bed construction

To investigate the effect of planting density on nutrient uptake, 9 small scale replicate subsurface flow CWs were installed in a single span polytunnel, 5 m × 20 m ($W \times L$) on an intensive marine fish farm in Pwllheli, North Wales, UK. Each CW had a 4 m^2 surface area and 1.2 m^3 volume (1 m × 4 m × 0.3 m, $W \times L \times H$). The CWs were scaled down replicas of those described in detail by Webb et al. (2012) and were laid out in a randomised block design, with the polytunnel divided into 3 sections and each CW type (high-/low-density planting and unplanted control) was represented in each of these (Fig. 1). In those beds designated for high-density planting, the mixed M grade quarry sand layer was reduced to 60 mm depth. In addition, the original irrigation and drainage system was modified enabling the separate supply of waste water to and discharge from each group of 3 CW (Fig. 1).

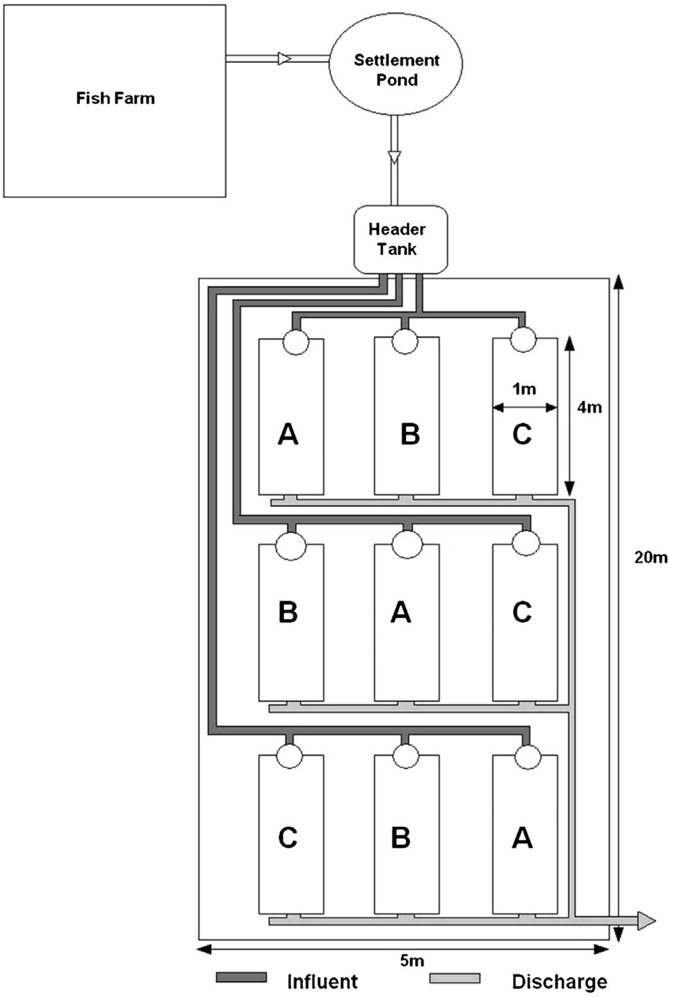

Fig. 1. A schematic representation of the layout of the replicate constructed wetlands. The polytunnel was split into 3 blocks and each constructed wetland type (A = high-density, B = low-density, C = control) was present in a section of each.

2.2. Plant production

Germination and early growth took place in a controlled environment greenhouse using *S. europaea* agg. (L) seeds sourced from 3rd generation cultivated plants under a 16:8 light:dark photoperiod. The minimum temperature was maintained at 25 °C during the light period and 20 °C during the dark period.

2.3. High-density planting system

In the high-density planting treatment, injection moulded polypropylene ‘Empot’ carrier trays, 555 mm × 310 mm × 30 mm ($L \times W \times H$) (http://www.lbsgardenwarehouse.co.uk, Ref. DTRS918) were lined with 17 g m^{-2} geotextile (http://www.lbsgardenwarehouse.co.uk, frost protection fleece Ref. R-F2050) and filled with ≤60 mm, mixed M grade quarry sand. *S. europaea* seeds were sown directly onto the sand surface to replicate high-density aggregations and irrigated with fresh water until germination at which point they were grown hydroponically in a Tropicmarin© saline solution (salinity of 10) with Phostrogen© soluble plant feed (N:P:K 14:10:27 + trace elements; Bayer CropScience Ltd., Cambridge, UK). Two months after germination, trays were transported to the experimental system and placed in three