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Growth and biomass production of different plant species in two different constructed wetland systems in Sicily

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Abstract

Constructed wetlands (CWs) could play a strategic role in wastewater reclamation and reuse in arid and semiarid regions, such as the Mediterranean area. The aim of this study was to analyse the phytoremoval effectiveness of *Phragmites australis* and spontaneous plant species (SPS) in two CW systems: a horizontal (H-SSF) and a vertical (V-SSF) subsurface flow. *P. australis* showed a higher biomass growth than SPS and always covered 100% of the bed's surface. The H-SSF system was more suitable for enhancing biomass growth of *P. australis* (4701 g m^{-2} as compared to 3088 g m^{-2} detected in the V-SSF CWs) whereas V-SSF of SPS (1700 g m^{-2} and 100% total cover as compared to 240 g m^{-2} and 40% total cover observed in H-SSF). SPS included species belonging to different botanical families in relation to the system adopted. Some of these species (i.e. *Phalaris* spp. and *Chrysantemum segetum*) were dominant in aboveground floral composition. Beds with SPS showed the same efficiency of the *Phragmites* ones in TSS, COD and pathogen removal. Phragmites was more effective than SPS in removing BOD_5 (in horizontal system), total phosphorus and nitrates. V-SSF system was more effective than H-SSF in removing total nitrogen. SPS presence did not decrease the efficiency of unplanted beds. Irrespective of the different plant species covering the beds, CWs were overall efficient in removing pollutants confirming their potential as an economic alternative to traditional urban wastewater treatments in small and medium-sized communities.

Keywords: Constructed wetlands; *Phragmites australis (Cav.)*,Trin.ex Steudel; Spontaneous plants species; Horizontal flow; Vertical flow

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1. Introduction

Constructed wetlands (CWs) are engineered systems designed to treat wastewater and an alternative to the more widespread conventional treatment technologies using higher energy inputs [1]. Unlike natural wetlands, depuration processes in CWs are performed under more controlled environments, which assure greater efficiency and regular phytodepuration activity across the entire bed [2]. Moreover, in Mediterranean basin, CWs could play a strategic role in wastewater reclamation and reuse especially in the areas where agriculture is largely dependent on irrigation. Very successful experiences with CWs have been reported in Jordan [3], France, Spain, Portugal, Morocco, Italy, Egypt, Israel, Slovenia, Croatia, Greece and Turkey [4].

Research into CWs has largely dealt with technological design where the primary issues were the inlet and outlet loads [5]. However, phytodepuration process effectiveness is strongly dependent on biological and physiochemical processes induced by the interaction of plants, microorganisms, substrates and pollutants. Studies performed to gain a better comprehension of these interactions may help to enhance CW effectiveness.

Plants suitable for use in CWs should be able to grow in water or under hypertrophic waterlogged conditions [6] and be well adapted to local climatic conditions, pests, diseases and pollutants. Moreover plants must be readily propagated, establish easily, and spread and grow rapidly. In addition, they must exhibit a high pollutant removal capacity, either through direct assimilation and storage, or indirectly by enhancement of microbial transformations such as nitrification (via root-zone oxygen release) and denitrification (via production of carbon substrates).

Currently, the most used plants in CWs are common reed (*Phragmites australis* (Cav.) Trin. ex Steud.), rushes (*Juncus* spp.), bulrushes (*Scirpus* spp.), narrow-leaved cattail (*Typha angustifolia* L.), broad-leaved cattail (*Typha latifolia* L.), yellow flag (*Iris pseudacorus* L.), sweet flag (*Acorus calamus* L.), reed grass (*Glyceria maxima* (Hartm.) Holmb.) and *Carex* spp.

Few studies have investigated the influence of native plant communities in CWs, despite the well-documented high suitability of many macrophytic plants in such systems. The use of plants which have been adapted to specific CW conditions will continue to remain an important topic of future research.

The present study was part of a larger investigation into management options for enhancing biological and nutrient removal from wastewater using CW technology (AQUATEC project, www.ponaquatec.com) in a South Italian small communiy representative of the Mediterranean environment [7].

The purpose of this study was to evaluate the effectiveness of two CWs (H-SSF and V-SSF) while comparing *P. australis* with spontaneous plant species (SPS) in treating wastewater.

2. Materials and methods

2.1. Site description

The experimental facility used in this investigation is located in San Michele di Ganzaria (Eastern Sicily – Italy −37°16′N, 14°25′E–350 m a.s.l.) and is operating from June 2004. This CW plant treated wastewater from the rural community of about 5000 inhabitants [8].

2.2. Pilot plant description

Four parallel systems consisted of two subsurface flow beds connected in series (Fig. 1). The CWs were designed to treat effluent from either the primary or the secondary settler of a conventional wastewater treatment plant (trickling filters). Wastewater from the effluent of the primary or secondary treatment unit is first stored in a 500-l tank, and then diverted to the

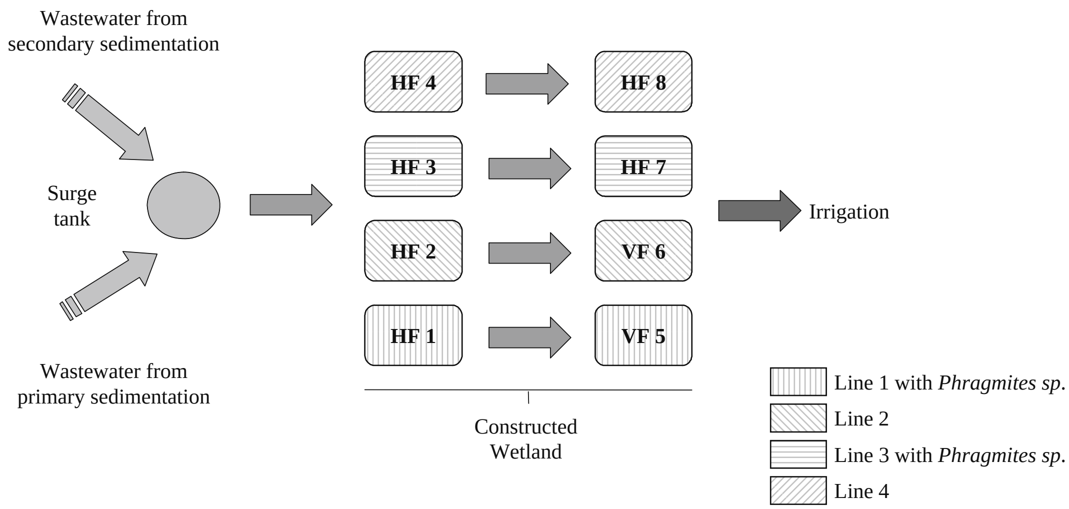

Fig. 1. Layout of pilot plant located in San Michele di Ganzaria (Sicily, Italy).

four systems. The first stage consisted of four horizontal subsurface flow beds (H-SSF 1–4). The second stage contained vertical flow beds operating for two systems (V-SSF 5 and 6) and horizontal subsurface flow beds for the other two (H-SSF 7 and 8). *Phragmites* spp. with an initial density of four rhizomes per m^2 were planted in two systems (one and three); in the other two (two and four) no planting occurred and spontaneous plant species (SPS) developed. Each bed was rectangular with a surface area of $4.5\,m^2$ ($1.5\,m \times 3.0\,m$) and was constructed of concrete lined with an impermeable membrane. The horizontal flow beds had slopes of about 1% and were filled, to an average depth of 0.6 m, with volcanic gravel having a gravel size of about 10–15 mm. The vertical flow systems were filled with two different medium layers: volcanic sand (about 0.06–4 mm) as the main layer for a depth of 0.5 m at the upper part of the filter bed and coarse volcanic gravel as the drainage layer (about 16–32 mm, 0.25 m depth). Between the horizontal and the vertical beds in systems one and two there was a 90-L tank containing a pump and a water level sensor for intermittent loading of the vertical bed. Loading occurred every 2 to 2.5 h. The final effluent from the wetlands was used for the irrigation of a green area near the pilot plant. In this study the pilot plant was used as secondary treatment (February 2005–May 2005).

2.3. Plant biomass

Three samples of 10 plants each were collected at the opposite sides and at the middle of each bed. Samples were taken at the end of May, almost at full maturity of *P. australis*.

Biomass dry weight was determined by drying plant tissue samples in a thermo-ventilated oven at 65°C until constant weight was reached. SPS were bulked for each botanical genus before drying.

2.4. Water analyses

From July 2004 to May 2005, every 15 days, wastewater samples were collected at the inlet and outlet of each stage of the treatment system. The samples were analysed for the following chemical–physical parameters: temperature, pH, EC, TSS (105°C), BOD_5, COD, TN, N-NO_3 and TP. The following microbiological parameters were also evaluated: faecal coliforms, *Escherichia coli*, faecal streptococci and *Salmonella*. The chemical and microbiological parameters were measured in the laboratory according to the standard methods [9]. BOD_5 and COD of CWs influent and effluent were evaluated on water samples filtered by GF/C Whatman glass fibre. EC, pH and temperature were further controlled *in situ*. *Salmonella* was measured according to the methodology proposed by Giammanco and co-workers [10]. The percentage concentration decrease efficiency was evaluated according to the formula proposed by the International Water Association [11]:

$$E = \frac{C_i - C_o}{C_i} \cdot 100$$

E = percentage concentration decrease efficiency (%)
C_i = inlet concentration (mg/L)
C_o = outlet concentration (mg/L).

2.5. Statistical analyses

In a completely randomized block design, the effects of the following factors were analysed: plant species (*P. australis* and spontaneous plant species [SPS]) colonizing the beds in the first stage of the experimental facility, and plant species (previously described) vs. phytodepuration systems (H-SSF and V-SSF) in the second stage. The differences in pollutant removal efficiency, among the four line systems, were also statistically assessed.

Data were statistically analysed by ANOVA. Three independent samples (replications) of each examined parameter were collected from each bed for each combination of the main factors examined. Least significant differences were calculated when the F test was significant at the 0.05 or 0.01 probability levels. Percentage data were arcsine $\sqrt{\%}$ transformed before statistical analysis. Actual percentages are shown.

3. Results and discussion

3.1. Biomass production and floral composition

In the first and second stages, dry biomass produced by *P. australis* was significantly (for $P \leq 0.05$) higher (7929 and 3894 g m^{-2}) than that produced by SPS (715 and 970 g m^{-2}). The H-SSF system was more effective in promoting growth and biomass (4701 g m^{-2}) in *P. australis* (100% total cover), whereas V-SSF unit showed greater growth in SPS (1770 g m^{-2}) (Fig. 2). Since the dissolved oxygen (DO) concentration in water outflow was always less than 1 mg/L in H-SSF systems, while a mean concentration of 4–5 mg/L was observed in the V-SSF systems, the latter system probably provided the most suitable root aeration conditions for SPS as also shown by the 100% covering of the surface.

Even in the most effective system for *P. australis* (H-SSF system), in the second set of beds, there was a 39% decrease in total biomass produced compared to the first stage. This effect was probably due to the higher nutrient content in the wastewater flowing through the first-stage beds.

There was a significantly higher surface cover in vertical system (100%) vs. the horizontal one (46%) with the self-propagated plants. Among the species colonizing the H-SSF system, *Senecio vulgaris* (L.) and *Silybum marianum* (L.) represented 38% of the total biomass while *Chrysanthemum* spp. and *Phalaris* spp. represented 30% of the total biomass observed in the V-SSF unit (Figs. 3 and 4). Among these plant species *Phalaris* spp. is particularly interesting since another genotype belonging to the same genus, *Phalaris arundinacea*, is widely adapted to constructed wetland conditions [2,12].

3.2. Wastewater treatments efficacy in relation to the plant species colonizing and CWs systems

Nutrient and pollutant removal are indicated in Fig. 5. TSS removal in all systems exceeded

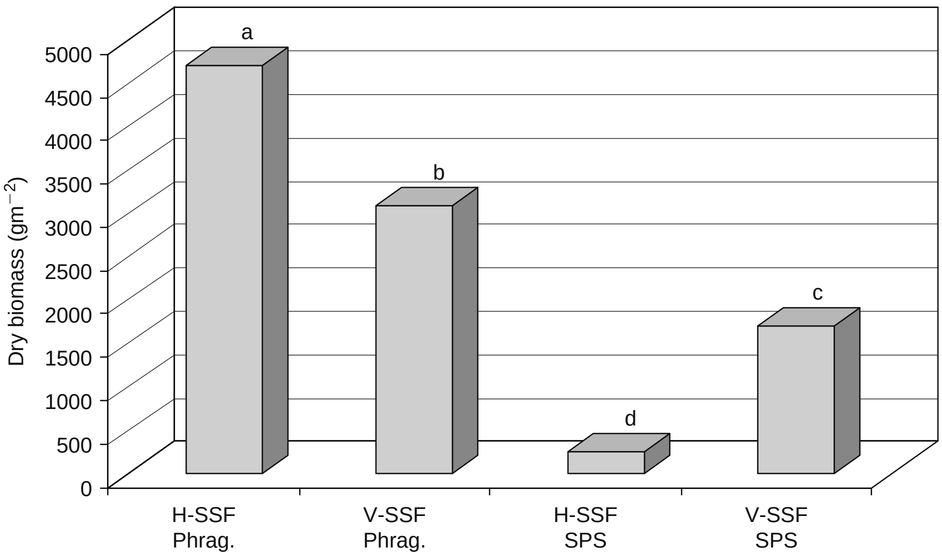

Fig. 2. Biomass produced by *Phragmites* and SPS grown in the second stage in relation to the different systems. Different letters indicate significant differences for $P \leq 0.05$.

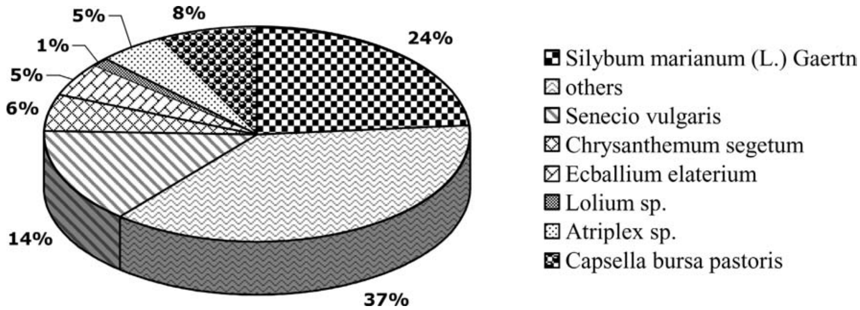

Fig. 3. Incidence of plant species dry biomass in the H-SSF system. Total dry biomass produced in the H-SSF bed is 241 g.

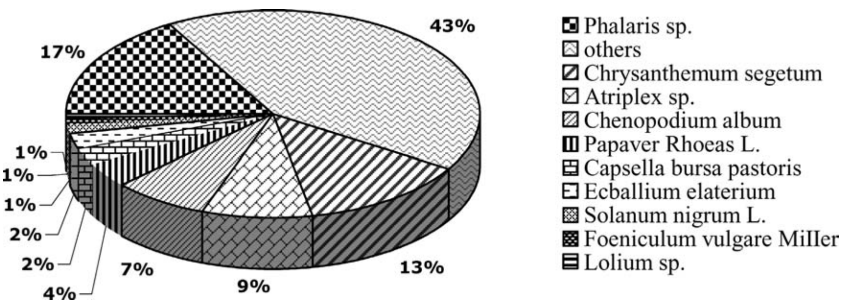

Fig. 4. Incidence of plant species dry biomass in the V-SSF system. Total dry biomass produced in the V-SSF bed is 1701 g.

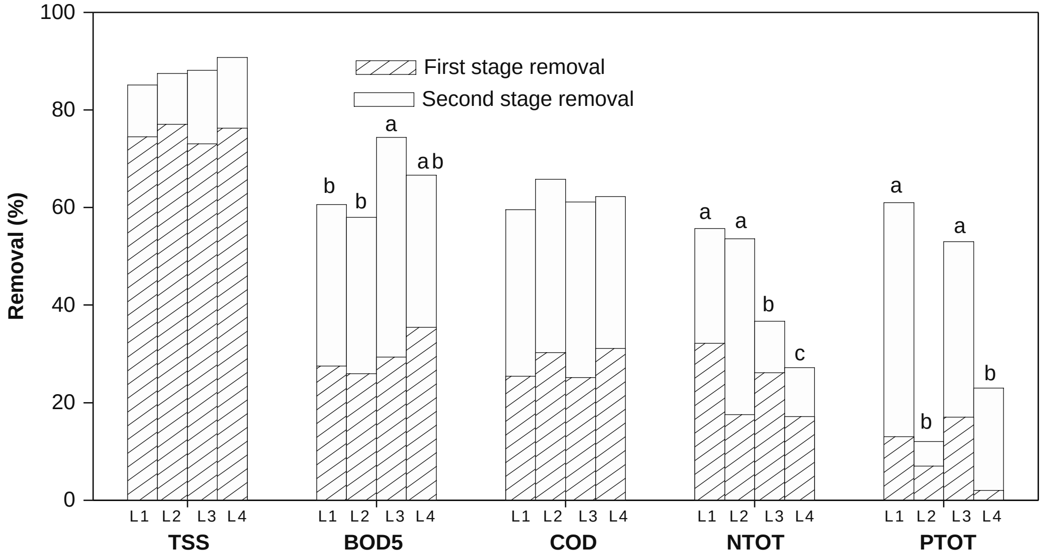

Fig. 5. Removal percentage of the main physical–chemical parameters. Systems one (L1) and three (L3) are vegetated with *Phragmites*; systems two (L2) and four (L4) are vegetated with spontaneous plant species. Different letters indicate significant differences for $P \leq 0.05$.

85%. The greatest removal was in the first stage of SPS beds (77% removal) compared to *P. australis* (74%). In the second stage of beds, the H-SSF removed more (+15%) than the V-SSF (+10%), regardless of the vegetation treatment. BOD_5 removal was the highest in system three (74%) and the lowest (61%) in systems one and two, with no significant difference in effectiveness between SPS and *P. australis* in the first stage. In the second stage, a significant interaction was observed between the phytodepuration systems and the plant species. *P. australis* gave the highest BOD_5 removal when grown in the horizontal bed.

COD removal did not vary in relation to the studied factors and was 61% on average in the four systems. Total nitrogen removal was 54% on average in the two systems where the second bed was vertical, whereas it did not exceed 37% when the second one was horizontal. This agrees with the results of Hamouri *et al*. [13], which attributed a low nitrogen removal to the H-SSF system due to the low oxygen availability for nitrogen oxidation in this system.

The nitrate mean concentration in the first stage of common reed beds (HF1 and HF2) was 2 mg/L and 0.26 mg/L, respectively, in inflow and outflow with a mean removal of about 87%, while in SPS beds (HF2 and HF4) it was 2 mg/L and 0.60 mg/L, respectively, in inflow and outflow with a mean removal of about 70%; thus, *Phragmites* seems to have a better nitrate removal performance. Total phosphorus removal averaged 57% in *P. australis* covered beds and was negligible in both SPS bed sets (12% in system one and 23% in system four). The P removal mostly occurred in the second sets of beds of system one (49%) and system three (36%).

More than 97% faecal coliforms, *E. coli* and faecal streptococci were removed (Table 1) in all systems. More than 91% of microorganisms were removed in the first stage of the experimental facility. The removal efficiency of *Salmonella* was always 100%.

Table 1
Mean removal efficiencies of the pilot-plant two-stage CWs

Treatment	System*	Stage	Mean removal efficiency (%)		
			CF	*E. coli*	SF
Secondary	1	1 (HF)	94.16	94.89	94.63
		2 (VF)	5.41	4.70	4.97
		1 + 2	99.57	99.59 **a**	99.60 **a**
	2	1 (HF)	91.42	92.33	92.60
		2 (VF)	5.58	4.85	4.99
		1 + 2	97.00	97.18 **b**	97.59 **b**
	3	1 (HF)	91.35	92.91	93.92
		2 (HF)	8.39	6.86	5.89
		1 + 2	99.75	99.77 **a**	99.81 **a**
	4	1 (HF)	92.30	94.04	93.77
		2 (HF)	5.35	3.71	4.71
		1 + 2	97.65	97.76 **ab**	98.48 **ab**

*Systems one and three are vegetated with *Phragmites*; systems two and four are vegetated with spontaneous plant species.
Within each column, system means followed by different letters are significantly different ($P \leq 0.05$).

4. Conclusions

In the first and second stages, *P. australis* developed greater biomass than SPS and covered 100% of the bed surface. The H-SSF was more suitable for *P. australis*, while V-SSF for SPS (100% covered surface) provided more suitable root aeration conditions for these plants. SPS belonging to different botanical families grew in unplanted beds. Among the recognized species grown in the vertical bed, *Phalaris* spp. and *Chrysantemum segetum* showed the highest incidence on floral composition. SPS showed the same efficiency in TSS, COD and pathogen removal as *Phragmites*. Common reed, however, was more effective than SPS in removing BOD_5 (in horizontal system), total phosphorous and nitrates, which may otherwise pollute surface and ground waters. The V-SSF was more effective than the H-SSF in removing total nitrogen.

The SPS development did not decrease the efficiency of unplanted beds. Knowledge gained regarding the interaction of the plant–phytodepuration system (horizontal or vertical) can be used to improve phytoremoval efficiency and to reduce CW management costs. Regardless of the plant species covering the beds, the pilot plant was efficient in removing some pollutants and confirmed the potential of CWs as an economic alternative to conventional urban wastewater treatment technologies in small and medium-sized communities. Further improvement in the CW systems is requested by Italian regulation (DM 185/03) for microorganism removal (*Escherichia* and *Salmonella*) when CW effluents are reused for irrigation.

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