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Italian Journal of Agronomy 2020; volume 15:1602

Ornamental plants for floating treatment wetlands: Preliminary results

Alberto Barco, Maurizio Borin

Department of Agronomy, Food, Natural Resources, Animals and Environment (DAFNAE), University of Padova, Agripolis Campus, Legnaro (PD), Italy

Abstract

Floating treatment wetlands (FTWs) represent a novel eco-technology for the treatment of different types of wastewaters in natural or artificial water bodies, through the use of traditional rooted emergent macrophyte species supported by floating rafts. Although many studies have reported the treatment performances of FTWs, showing an excellent aptitude for removing nutrients, heavy metals as well as suspended solids, the investigation of vegetation has not received much attention up to now, especially for herbaceous ornamental plant species that could form an interesting opportunity to improve water quality and the esthetic-ornamental value of urban water bodies. For this reason, a pilot scale FTW was installed in Northern Italy to assess the growth performances of eleven wetland species having ornamental features: *Canna indica* L., *Pontederia cordata* L., *Thalia dealbata* Fraser ex Roscoe, *Acorus calamus* L., *Juncus effusus* L., *Iris laevigata* L., *Mentha aquatica* L., *Oenanthe javanica* (Blume) DC., *Caltha palustris* L., *Sparganium erectum* L. and *Zantedeschia aetiopica* (L.) Srengel. For these species, a suitability index was elaborated that considers plant survivability, above-mat biomass production, nitrogen uptake, root length and root-shoot ratio. On this basis, the results obtained clearly indicated that *C. indica*, *P. cordata* and *T. dealbata* were the most suitable species for FTW due to their high vigor and colonization of the floating mats (1638.9 g m^{-2}, 483.4 g m^{-2}, 566.1 g m^{-2} of above-mat dry biomass, respectively; 38.8 cm, 62.0 cm, 43.8 cm root length, respectively; 0.8, 0.9, 1.2 root-shoot ratio, respectively), survival (100%), nitrogen uptake (15.1 g m^{-2}, 15.0 g m^{-2}, 15.7 g m^{-2} respectively). On the contrary, *A. calamus*, *S. erectum* and *Z. aetiopica* did not present adequate features for use in FTWs.

Correspondence: Alberto Barco, Department of Agronomy, Food, Natural Resources, Animals and Environment (DAFNAE), University of Padova, Agripolis Campus, viale dell'Università 16, 35020 Legnaro (PD), Italy.
E-mail: albertobarco92@gmail.com

Key words: Ornamental plants; artificial floating islands; biomass production; root-shoot ratio; nitrogen uptake; plant survival; suitability index.

Acknowledgements: Research conducted with the financial support of MIPAF OIGA 2009 Project *Reproduction, cultivation and evaluation of vegetal species for environmental purposes* and the contribution of P.A.N. Spinoff of the University of Padova.

Received for publication: 1 February 2020,
Revision received: 14 March 2020.
Accepted for publication: 28 March 2020.

Italian Journal of Agronomy 2020; 15:1602
doi:10.4081/ija.2020.1602

Introduction

Floating treatment wetlands (FTWs) represent a recent alternative within free water surface constructed wetlands, able to treat a large volume of wastewater in already existing natural or artificial water bodies (De Stefani *et al*., 2011; Faulwetter *et al*., 2011; Mietto *et al*., 2013; Chang *et al*., 2013; Borne, 2014; Borne *et al*., 2014; Barco and Borin, 2017; Pappalardo *et al*., 2017; Tharp *et al*., 2019). This novel approach in the field of wastewater treatment consists of the use of self-buoyant platforms on which the traditional un-floating rooted macrophyte species are installed, and expand their root systems directly in the water column (Hedley and Tanner, 2006).

FTWs have been used to treat different wastewaters, such as those collected from urban districts (Van de Moortel *et al*., 2010; Chua *et al*., 2012; Mietto *et al*., 2013; Duan *et al*., 2016; Barco and Borin, 2017), eutrophic water (Hu *et al*., 2010; Quing *et al*., 2016; Li and Guo, 2017; Olguin *et al*., 2017), river (Zhou and Wang, 2010; De Stefani *et al*., 2011; Zhu *et al*., 2011; Duan *et al*., 2016; Saeed *et al*., 2016; Pappalardo *et al*., 2017; Gao *et al*., 2017; Dal Ferro *et al*., 2018; Shahid *et al*., 2018), stormwater run-off (Ladislas *et al*., 2015; Lynch *et al*., 2015; Hartshorn *et al*., 2016; Ge *et al*., 2016; McAndrew *et al*., 2016; Urakawa *et al*., 2017; Zanin *et al*., 2018) and agricultural run-off (Spangler *et al*., 2019).

Interesting performances have been obtained in term of nutrients, organic matter and suspended solids removal rates, as previously reviewed by Chen *et al*. (2016), Bi *et al*. (2019) and Rehman *et al*. (2019). The correct selection of vegetation provides different functions: root filtering effect against suspended solids, oxygen transferal through aerenchym from aerial tissues to root system, absorption of nutrients and heavy metals, surface for microbial biofilm growth, releasing of antimicrobic compounds, phytochelatins and phytometallopores and rhizodeposition products (Vymazal, 2013).

Although different plant species belonging to several botanical families (*Poaceae*, *Typhaceae* and *Cyperaceae*) have been adopted in many FTWs built all over the world, the choice mainly regards a restricted group of un-floating rooted emergent aerenchymatous macrophytes characterized by an excellent capability to survive under hydroponic conditions (*Carex* spp., *Phragmites australis*, *Typha latifolia*), even at high pollutants loads (Ibrahim *et al*., 2017; Rehman *et al*., 2019). More recently, FTWs have been installed with the double aim of ameliorating the physic-chemical quality of water bodies and the necessity to improve their esthetic-ornamental values, especially in urban settings (Zanin *et al*., 2018). This latter requirement could be achieved in different ways, such as: i) the selection of species characterized by abundant and colorful flowering; ii) a mixture of different species with variously colored flowers, perhaps with different blooming times; iii) the use of species with aesthetic foliage characteristics (*e.g*. shape, color, colored and evident veins, mottling), or, iv) transplanting species that maintain a green coverage of floating mats throughout the year (Figure 1). In this scenario, different dual-purpose species (water purification and ornamental value) have been used in FTWs. The most frequent study cases came from China, USA and Italy and investigated the growth of *Iris* spp., *Carex* spp., *Oenanthe* spp., *Canna* spp. and *Pontederia cordata* (Figure 2). Focusing attention on *I. pseudacorus*, Keizer-Velk *et al*. (2014) harvested more than 1071 g m^{-2} of above-mat dry biomass (300 g 0.28 m^{-2}) and about 714 g m^{-2} of below-mat dry biomass (200 g d.m. 0.28 m^{-2}) in a commercial nutrient solution. Pavan *et al*. (2015) reached less than 200 g m^{-2} dry matter (d.m.) and about 500 g m^{-2} d.m. of above-mat biomass after the first and second growing seasons, respectively, treating diluted digestate liquid fraction, whereas Barco and Borin (2017) reported excellent biomass production in municipal wastewater with 3700 g m^{-2} of above-mat dry biomass (shoot height 135.9 cm) and 20200 g m^{-2} of below-mat d.m. (root length 46.3 cm). Pappalardo *et al*. (2017) obtained the worst results treating agricultural run-off with 20.2 g m^{-2} of above-mat dry biomass (shoot height 38.4 cm) and 86.7 g m^{-2} of below-mat d.m. (root length 76.4 cm), due to a very low nutrients concentration in the water.

Wang *et al*. (2015) tested the growth performances of *P. cordata* in an urban retention pond, where they harvested about 2.3 g $plant^{-1}$ of above-mat d.m. and more than 7.5 g $plant^{-1}$ of below-mat d.m. and measured maximum shoot height and root length of about 44 cm and 43 cm, respectively. Tharp *et al*. (2019) working in a stormwater retention pond obtained less than 10 g $plant^{-1}$ of above-mat d.m. and measured a maximum root length lower than 15 cm. Zhao *et al*. (2012) cultivated the species in an FTW to ameliorate eutrophic river water and obtained less than 1500 g m^{-2} of above-mat d.m. The growth of *Canna* was tested: i) in eutrophic river water where the species produced more than 1500 g m^{-2} of above-mat d.m. (Zhao *et al*., 2012); ii) in stormwater run-off wastewater where it reached a maximum root expansion in the water column of 25-50 cm (White and Cousins, 2013); and iii) in synthetic wastewater where the total length of plants ranged between 54.4 cm (about 40.6 cm of shoot height and 13.8 cm of root length) and 80.7 cm (about 58.7 cm of shoot height and 22 cm of root length) (Zhang *et al*., 2018).

Figure 1. Examples of ornamental plant species usually used in floating treatment wetlands, characterized by: i) colored flowers (top, from left, *Iris pseudacorus*, *Iris laevigata* and *Pontederia cordata*); ii) foliage aesthetic value (bottom, from left, *Canna indica* and *Acorus calamus*).

The performances of different species of the *Carex* genus were mainly assessed in stormwater run-off. Above-mat d.m. amounted to 71.7-191 g plant^{-1} for *C. stricta* (Winston *et al*., 2013) and 93-113 g plant^{-1} for *C. riparia* (Ladislas *et al*., 2013). Similarly, below-mat d.m. ranged from 86-115 g plant^{-1} for *C. riparia* (Ladislas *et al*., 2013) to 194.7-220.5 g plant^{-1} (root length 75 cm) for *C. virgata* (Winston *et al*., 2013). The behavior of *C. elata* was tested in Northern Italy, where it produced 266.9-565.7 g m^{-2} of above-mat d.m. (45.7-52.1 cm shoot height) and 166.2-442.6 g m^{-2} (66.2-64.8 cm root depth) of below-mat d.m. (Pappalardo *et al*., 2017).

The adaptability of *O. javanica* was evaluated in FTWs installed to treat river water. In this case, the biomass produced showed a wide fluctuation among trials with minimum values of 96.8 g m^{-2} and 66.8 g m^{-2} of above- and below-mat d.m., respectively (Zhu *et al*., 2011) and maximum values of 808 g m^{-2} and 677.5 g m^{-2} of above- and below-mat d.m., respectively (Zhou and Wang, 2010).

Given this state of the art, to the best of our knowledge, no other studies have reported the growth performances of more than 4 ornamental species within the same FTW installation. For this reason, the current paper aimed to assess the growth parameters (shoot height, root length, above-mat biomass production) as well as the survivability of eleven different wetland species with ornamental value, installed in a pilot scale FTW in Northern Italy.

Materials and methods

Experiment description

The experiment was conducted at the *Lucio Toniolo Experimental Farm* of the University of Padova, Veneto Region, North-eastern Italy (Lat. 45°11'N, 11°21'E) between December 2009 and July 2010. The experimental site consisted of a north-south orientated greenhouse facility (25 m length, 12 m width, 6 m height) covered with a transparent polyethylene plastic film, in which a pilot FTW was installed. The constructed FTW was composed of 3 identical waterproofed polyethylene basins (Fito Star®) (3 replications) (2.5 m length, 2.0 m width, 0.6 m height, volume 3 m^3 each). The upper part of each basin was provided with a PN10 PVC plastic pipe (50 mm external diameter) connected with an electro-valve and flow-meter to provide and measure the tap water load, while a PN16 PVC plastic valve (50 mm diameter) was installed in the bottom to allow basin discharge. Each basin surface was covered by 9 Tech-IA floating mats, for a total of 27 floating mats in the experiment. A Tech-IA® floating mat is made of ethylene vinyl acetate (EVA), a recyclable and non-toxic material, with high mechanical, chemical, biological and weather resistance (De Stefani *et al*., 2011). Each Tech-IA® floating element is rectangular in shape (45x93 cm), with eight (15x15 cm) quadrangular grids for anchoring plants. It weighs 1.7 kg and supports more than 20 kg weight.

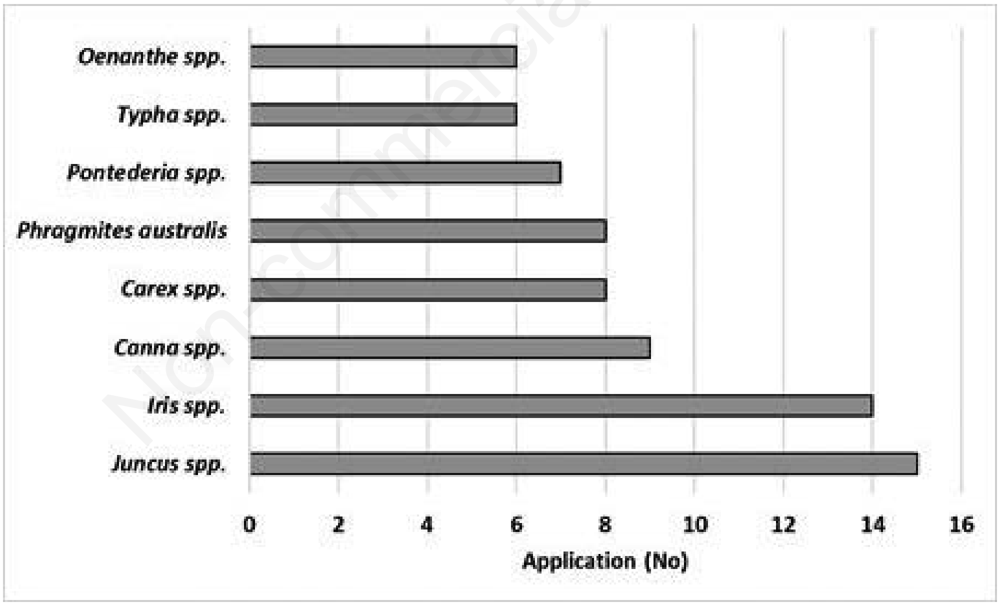

Figure 2. Number of applications of the main dual-purpose wetland species (ornamental value and wastewater treatment) around the world. Iris spp: De Stefani (2012), Mietto *et al.* (2013), Pavan *et al.* (2015), Hartshorn *et al.* (2016), McAndrew *et al.* (2016), Quing *et al.* (2016), Barco and Borin (2017), Gao *et al.* (2017), McAndrew *et al.* (2017), Pappalardo *et al.* (2017), Wang *et al.*, (2017), West *et al.* (2017), Zanin *et al.* (2018), Sapngler *et al.* (2019 b). Oenanthe spp.: Zhou and Wang (2010), Hu *et al.* (2010), Zhu *et al.* (2011), Duan *et al.* (2016), Geng *et al.* (2017), Zanin *et al.* (2018). Canna spp: Zhang *et al.* (2014), Ge *et al.* (2016), Hartshorn *et al.* (2016), Quing *et al.* (2016), Saeed *et al.* (2016), Urakawa *et al.*, (2017), Zanin *et al.* (2018), Zhang *et al.* (2018), Spangler *et al.* (2019 b). Juncus spp.: De Stefani *et al.* (2011), Ladislas *et al.* (2013), Ladislas *et al.* (2015), Lu *et al.* (2015), Lynch *et al.* (2015), Pavan *et al.* (2015), Hartshorn *et al.* (2016), McAndrew *et al.* (2016), McAndrew and Ahn (2017), Pappalardo *et al.* (2017), Urakawa *et al.* (2017), West *et al.* (2017), Chanc *et al.* (2019), Spangler *et al.* (2019 a), Tharp *et al.* (2019). Carex spp.: De Stefani *et al.* (2011), Ladislas *et al.* (2013), Ladislas *et al.* (2015), Mc Andrew *et al.* (2016), McAndrew and Ahn (2017), Pappalardo *et al.* (2017), Spangler *et al.* (2019 b), Tharp *et al.* (2019). Phragmites australis: De Stefani *et al.* (2011), De Stefani (2012), Mietto *et al.* (2013), Pavan *et al.* (2015), Saeed *et al.* (2016), Barco and Borin (2017), Li and Guo (2017), Sanicola *et al.* (2018). Pontederia spp.: Wang *et al.* (2014), McAndrew *et al.* (2016), McAndrew and Ahn (2017), Olguin *et al.* (2017). Chanc *et al.* (2019), Spangler *et al.* (2019 a), Tharp *et al.* (2019). Typha spp.: De Stefani *et al.* (2011), Chua *et al.* (2012), De Stefani (2012), Lu *et al.* (2015), Pavan *et al.* (2015), Zanin *et al.* (2018).

The growth and development of eleven different ornamental species, whose botanical description is reported in Table 1, were studied: *Iris laevigata* Fisch., *Pontederia cordata* L., *Canna indica* L., *Thalia dealbata* Fraser ex Roscoe, *Mentha aquatica* L., *Juncus effusus* L., *Zantedeschia aetiopica* (L.) Srengel, *Sparganium erectum* L., *Acorus calamus* L., *Oenanthe javanica* (Blume) DC. and *Caltha palustris* L.

The experiment began in December 2009 with the transplanting of 8 species (1 species per floating mat; 1 floating mat per basin remained un-vegetated). At this purpose, *P. cordata*, *C. indica*, *T. dealbata*, *I. laevigata*, *J. effusus*, *Z. aetiopica* and *S. erectum* were transplanted in the floating mats as pieces of rhizome whereas *M. aquatica* as pieces of stolon (20-25 cm length, 3 living sprouts each) obtained from specialist plant nurseries located near the experimental site (transplanting density 2 plants floating mat^{-1}, 4 plants m^{-2}). A completely randomized experimental design was adopted in which each studied species was replicated three times.

After transplanting there was a period of adaption in which plants remained in contact with tap water without any fertilizer supply, then after the sprouting phase, two consecutive fertilizer applications were done, the first one on March 17th 2010, the second on April 1st 2010. For this purpose, a prepared nutrient solution was used and gradually added to each basin until an electrical conductivity of about 1500 µS cm^{-1} was reached. The chemical features of the nutrient solution are the following: KCl 1.86 mg L^{-1}; H_3BO_3 0.77 mg L^{-1}; $MnSO_4*H_2O$ 0.17 mg L^{-1}; $ZnSO_4*7\ H_2O$ 0.29 mg L^{-1}; $CuSO_4*5\ H_2O$ 0.06 mg L^{-1}; H_2MoO_4 (85% MoO_3) 0.04 mg L^{-1}; HNO_3 214 mg L^{-1}; $Ca(NO_3)_2$ 216 mg L^{-1}; NH_4NO_3 63.6 mg9 L^{-1}; KH_2PO_4 136 mg L^{-1}; K_2SO_4 118 mg L^{-1}; $MgSO_4$ 24.6 mg L^{-1}; KNO_3 54 mg L^{-1}; FeEDTA (6%) 7.5 mg L^{-1}.

Due to the fact that at the beginning of the growing season, *Z. aetiopica* and *S. erectum* did not survive, even though repetitive transplantations were performed, they were replaced by *A. calamus* and *O. javanica,* whereas *C. palustris* was installed in the un-vegetated floating mats. These species were chosen in the same phenological phase of previously installed species and transplanted on April 1st 2010 as 30 cm tall plants (transplanting density 2 plants floating mat^{-1}, 4 plants m^{-2}).

Monitored parameters

During the experimental period, water pH, electrical conductivity (EC) (measured at 10 cm depth) and dissolved oxygen (DO) (recorded at 10 cm and 50 cm depths of each basin) were measured in situ once a week using a multiparametric probe (Hach-Lange) according to the standard method (APHA, 1998).

Water and air temperature values were measured once a week using a portable thermometer (Ecomorma s.a.s., FT2300) to assess the environmental conditions which affected plants vegetative cycle.

Water integration was done by adding tap water seven times during the experimental period and water volumes supplied were measured through a flowmeter to assess the water consumed by vegetation evapotranspiration.

Plants biometric characteristics, particularly shoot height (cm) and root length (cm), were measured weekly in each floating mat over the entire experimental period through an extensible meter. Aerial fresh biomass production (g m^{-2}) was determined by harvesting plant biomass in each floating mat. The harvesting of veg-

Table 1. List of ornamental species used in the study and the correspondent botanic description.

Species	Family	Origin	Botanic description
Acorus calamus L.	*Acoraceae*	Asia	0.5-1.0 m height; linear leaves; light green-yellow flowers. Propagation: rhizome. Bloom: spring
Caltha palustris L.	*Ranunculaceae*	Temperate regions of the Northern Hemisphere	10–80 cm height; thick branching roots; 2-5 cm diameter yellow flower. Propagation: rhizome. Bloom: early spring-late summer.
Canna indica L.	*Cannaceae*	South America, Central America, southeastern United States	0.5 -2.0 m height; hermaphrodite flowers; decorative leaves and orange-red flowers; small, globular, black pellet seeds. Propagation: rhizome. Bloom: summer.
Iris laevigata Fisch.	*Iridaceae*	Japan	90-100 cm height, blue, purple or violet flowers with rotund, short, vertical petals. Propagation: rhizome. Bloom: early spring.
Juncus effusus L.	*Juncaceae*	Europe, Asia, Africa, North and South America	1.5 m height, lucid, bright green stems; green-brown inflorescence. Propagation: rhizome. Bloom: summer.
Mentha aquatica L.	*Lamiaceae*	Europe, northwest Africa and southwest Asia	Fleshy with fibrous roots (90 cm); ovate to lanceolate leaves; small pink-purple flowers. Propagation: stolon. Bloom: summer.
Oenanthe javanica (Blume) DC.	*Apiaceae*	East Asia, Australia	1 m height; fibrous roots from all nodes; leaves: aromatic, glabrous, sheath covering the stem; flowers: 5 white petals and 5 stamens. Propagation: rhizome. Bloom: summer.
Pontederia cordata L.	*Pontederiaceae*	America	Aquatic species; lucid leaves; blue-purple flowers. Propagation: rhizome. Bloom: late spring-early summer.
Thalia dealbata Fraser ex Roscoe	*Marantaceae*	Southern and central United States	Aquatic plant, 1.8 m height; leaves: blue-green, ovate to lanceolate; flowers: small, violet. Propagation: rhizome. Bloom: late summer.
Sparganium erectum L.	Typhaceae	Temperate regions of both the Northern and Southern Hemispheres	Aquatic, emergent stems with aerenchym; strap-like leaves; flowers: borne in spherical heads, hermaphrodite. Propagation: rhizome. Bloom: summer.
Zantedeschia aethiopica (L.) Srengel	*Araceae*	Southern Africa	Herbaceous, evergreen, 0.6–1 m height; leaves: arrow shaped, dark green; inflorescences: large with a pure white spathe and a yellow spadix. Propagation: rhizome. Bloom: beginning, till late spring.

etation was done on July 30th 2010, to maximize nitrogen uptake from water through plant above-mat biomass. Dry biomass production (g m^{-2}) was obtained by drying 100 g fresh tissue samples in a forced air oven at 65°C for about 48 hours, until constant weight was reached. Dry biomass was then milled to 2 mm and analyzed to quantify Total Kjeldhal Nitrogen (TKN) through titration (FAO, 2011). The total nitrogen content in above-mat tissues was obtained as the product between aerial dry biomass production and nitrogen percentage concentration. The root shoot ratio (root length/shoot height) was calculated on plants biometric characteristics in different phenological phases: sprouting (February 3rd 2010-March 16th 2010), shoot elongation/flowering (March 24th 2010-June 3rd 2010) and flowering-fruit development (June 10th 2010-July 30th 2010).

Plant survival, computed at harvesting time, was calculated as the ratio between number of living plants before harvesting and the corresponding number at the beginning of the growing season.

Although Silvestri *et al*. (2017) reported a multi-adaptive framework to select crops in paludicultural cropping systems, mainly basing on crops biological traits, biomass production and quality as well as aptitude to cultivation, no similar methodologies have been found for artificial floating islands. For this reason, a suitability index (SI) was elaborated to describe the capability of ornamental species to survive in FTWs.

It considers: i) plant survival at harvesting time (SR); the low survival of plants, due to scarce or absent capacity of adaptation to live with roots directly in the water column and/or to overcome winter frost, compromises the success of the system; ii) above-mat biomass production (AB) that estimates the potential of plants in removing pollutants; in fact, above-mat biomass can be harvested and consequently nutrients/pollutants can be removed; iii) nitrogen uptake by above-mat biomass (NU), to assess the capacity to remove N with harvesting; iv) maximum root length (RL), indicating the water column involved in depurative processes; v) average root-shoot ratio (R/S), to describe the balance between aerial and root organs and therefore, the risk that floating vegetated barriers overturn under wind pressure. This risk is higher in presence of tall plants with reduced root depth.

The variability of data (form minimum to maximum values) within each parameter considered in the SI calculation was divided into three equal classes, as shown in Table 2. An individual score was attributed for each class within each parameter (Table 2): i) from 0 to 2 for plant survivability where 0 (corresponding to plant survivability lower than 33.3%) represented the worst condition without any functionality of the FTW, whereas 2 the best ones with the prompt and complete establishment of vegetation; ii) from 1 to 3 for AB, NU, RL and R/S where 1 represented the worst whereas 3 the best conditions for the functionality of FTWs.

For all parameters, greater the score, greater the suitability of the species to be adopted in FTWs.

The SI was calculated through the following equation: $SI = SR \times (AB + NU + RL + R/S)$.

Statistical analysis

The normality of data was checked through the Bartlett statistical test, whereas the homoscedasticity through the Levene test. Collected data followed a normal distribution and the variance is homogeneous. For all studied species except for *Z. aetiopica* and *S. erectum* that did not survive till the end of the study, maximum plant biometric characteristics (shoot height and root length), above-mat biomass production, nitrogen percentage concentration as well as nitrogen content in above-mat dry biomass were statistically analyzed by one-way analysis of variance test (ANOVA) at $P<0.05$ and the differences between average values were detected by least significant difference (LSD) test ($P<0.05$). The regression between root length and shoot height was assessed through a simple regression analysis model ($P<0.05$).

Results and discussion

Water monitoring

During the entire experimental period, water pH ranged between 6.2 and 8.5 (Figure 3A). The average value of 7.0 was similar to values recorded at the inlet of other FTWs installed in the same area (pH 7.5: Barco and Borin, 2017; pH 7.4; Mietto *et al*., 2013), and was suitable for the functioning of FTW since the microbial processes of ammonification and nitrification proceed rapidly under this water pH (optimum pH for ammonification: 6.5-8.5, optimum pH for nitrification 6.6-8.0) (Vymazal and Kropfelova, 2008).

During the monitoring period, water EC irregularly varied between 826.3 µS cm^{-1} and 1489.3 µS cm^{-1}, average 1194.7 µS cm^{-1} (Figure 2B). Measured values were always higher than the optimal range for crop irrigation indicated for semi-arid regions by Ayers and Westcot (1994) and Bortolini *et al*. (2018) (EC lower than 700 µS cm^{-1}). The highest values were measured from March 11th 2010 to April 27th 2010 in correspondence to the two fertilization treatments (March 17th 2010 and April 1st 2010) (Figure 3B), as already confirmed in similar experimental conditions by West *et al*. (2017). In the following experimental period, the EC was reduced if compared to the previous period due to: i) the lack of other fertilization treatments; ii) the consequent dilution effect due to nutrients absorption by plant root systems and the increasing of water volumes added to compensate for losses through plant evapotranspiration (Figure 3B).

The DO ranged between 0.4 mg L^{-1} and 6.1 mg L^{-1} at 10 cm depth, and between 0.2 mg L^{-1} and 6.1 mg L^{-1} at the bottom of the basins (Figure 3C). In the first part of the experimental period (from February 3rd 2010 to April 15th 2010), the DO concentration did not follow any precise temporal trend, with an irregular fluctuation of values over time. On the contrary, from April 21st 2010 to

Table 2. Partition of data variability within the different parameters involved in the calculation of the suitability index.

Parameter	Class	Score	Range
Survivability (%)	1	0	< 33.3
	2	1	33.3-66.6
	3	2	> 66.6
Above-mat biomass production (g m^{-2})	1	1	< 1054.0
	2	2	1054.0- 2108.0
	3	3	> 2108.0
Nitrogen uptake (g m^{-2})	1	1	< 10.7
	2	2	10.7-21.4
	3	3	> 21.4
Root length (cm)	1	1	< 20.7
	2	2	20.7-41.3
	3	3	> 41.3
Root/Shoot ratio	1	1	< 0.4
	2	2	0.4-0.8
	3	3	> 0.8

July 16th 2010, DO concentration fluctuations reduced even though it was not completely stable either at the surface or on the bottom of basins (Figure 3C). Over the entire experimental period, DO concentration measured at the water surface was higher than on the bottom with average values of 2.6 mg L^{-1} and 2.4 mg L^{-1}, respectively (Figure 3C).

During the experimental period, air and water temperature followed a similar seasonal trend with a progressive increase from the beginning (in February 15.1±0.2°C and 15.4±0.4°C for air and water temperature, respectively) till the end of the study (in July 31.7±1.2°C and 28.6±1.1°C for air and water temperature, respectively) (Figure 4). Monthly air temperatures recorded in the study were always higher than those measured in open-air conditions of the same area (February: 5.0°C, March: 8.1°C, April: 13.8°C, May: 17.7°C, June: 21.9°C, July: 24.7°C), probably due to the greenhouse effect. In general, monthly water temperature was almost always lower than air one.

Water consumption by plants evapotranspiration followed the same monthly trend reported for air and water temperature (Figure 4). The lowest values were recorded at the beginning of the growing season (February and March, 24.7 mm on average) in correspondence to the sprouting phase, whereas the highest were obtained in June and July (72.3 mm on average) with the progressive increase of plant size, leaf area and consequent coverage of the floating mats. The monthly plants evapotranspiration obtained in the study was in line with seasonal values obtained in a stormwater retention pond where a FTW was installed (3.03 mm day^{-1} during spring, 3.32 mm day^{-1} during summer and 1.01 mm day^{-1} during winter) (Zanin *et al*., 2018) and in a free water surface constructed wetland (3.9 mm day^{-1} in spring and summer, 1.3 mm day^{-1} in autumn and winter) (Dal Ferro *et al*., 2018) located in the same area. Instead, other studies on wetland herbaceous species cultivated in soil or substrate conditions reported higher cumulative plant evapotranspiration values (1530.9 mm: Barco *et al*., 2018; 3000 mm: Borin *et al*., 2011) than that recorded in the current study (on average 290.7 mm). The relatively low evapotranspiration rates obtained in this study could be attributed to: i) the newly established vegetation in the FTW system which did not completely colonize the floating modules; and ii) the lack of evaporation from the water surface which was completely covered by the floating modules.

Biometric characteristics

The biometric characteristics of plant species measured over the monitoring period are reported in Figure 5. *C. indica*, *P. cordata*, *M. aquatica*, *T. dealbata* and *J. effusus* had earlier vegetative growth (February) if compared with open-air conditions in the same area (Pavan *et al*., 2015; Pappalardo *et al*., 2017), which occurs in mid-March, early April. In particular the relatively high air (15.4°C and 20.7°C on average in February and March, respectively) and water temperature (15.1°C and 16.4°C in February and March, respectively) values in the greenhouse, allowed the vegetative cycle to be anticipated by more than one month. For these species, the average shoot height and root length continuously increased from sprouting to harvesting time, reaching the highest average values at the end of the monitoring period (Figure 5). A similar temporal trend over the growing season (sprouting phase-harvesting period) in shoot elongation and root extension was reported for *C. flaccida* (shoot height and root length increased by 30 cm and 40 cm, respectively), *J. effusus* (shoot height and root length increased by 40 cm and 70 cm, respectively) (White and Cousins, 2013) and *P. cordata* (shoot height and root length increased by 10 cm and 20 cm, respectively) (Wang *et al*., 2015).

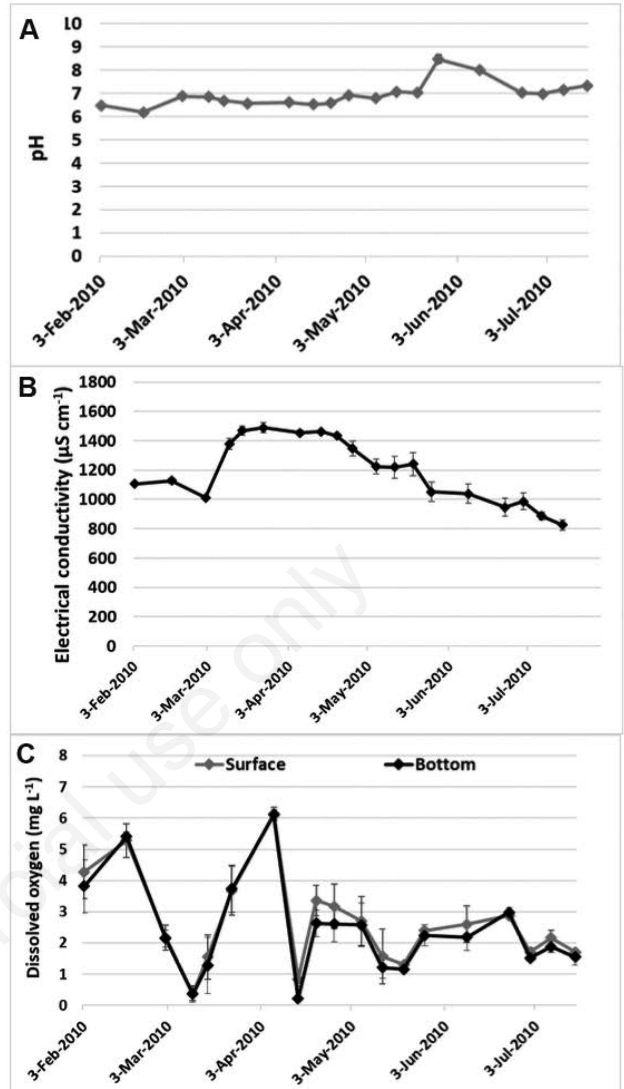

Figure 3. Evolution of A) water pH (measured at 10 cm depth), B) electric conductivity (µS cm^{-1}) (measured at 10 cm depth), ▪ water refills and Δ fertilization treatments C) dissolved oxygen concentration (mg L^{-1}) (measured at 10 cm and 50 cm depth) during the experimental period (average value±standard error).

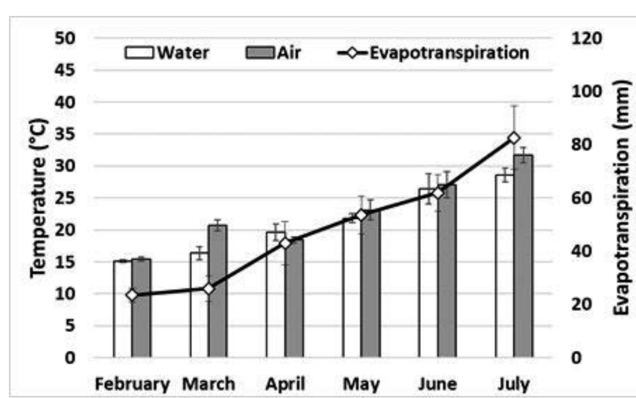

Figure 4. Monthly air and water temperature (°C) and evapotranspiration (mm) values measured in the experimental site (average value±standard error).

Similar to the other species, *I. laevigata* was characterized by a first phenological phase of shoot elongation (from February until June), with a peak value of 78.2±10.8 cm recorded just after blooming (3rd June), then by a progressive decreasing of shoot height until the harvesting period with senescence of the plant (Figure 5). On the contrary, the root length remained almost constant until mid-March and then progressively increased, reaching maximum development just before harvesting (43.3±14.5 cm) (Figure 5). The monitoring of biometric characteristics of *O. javanica*, *C. palustris* and *A. calamus* began relatively later with

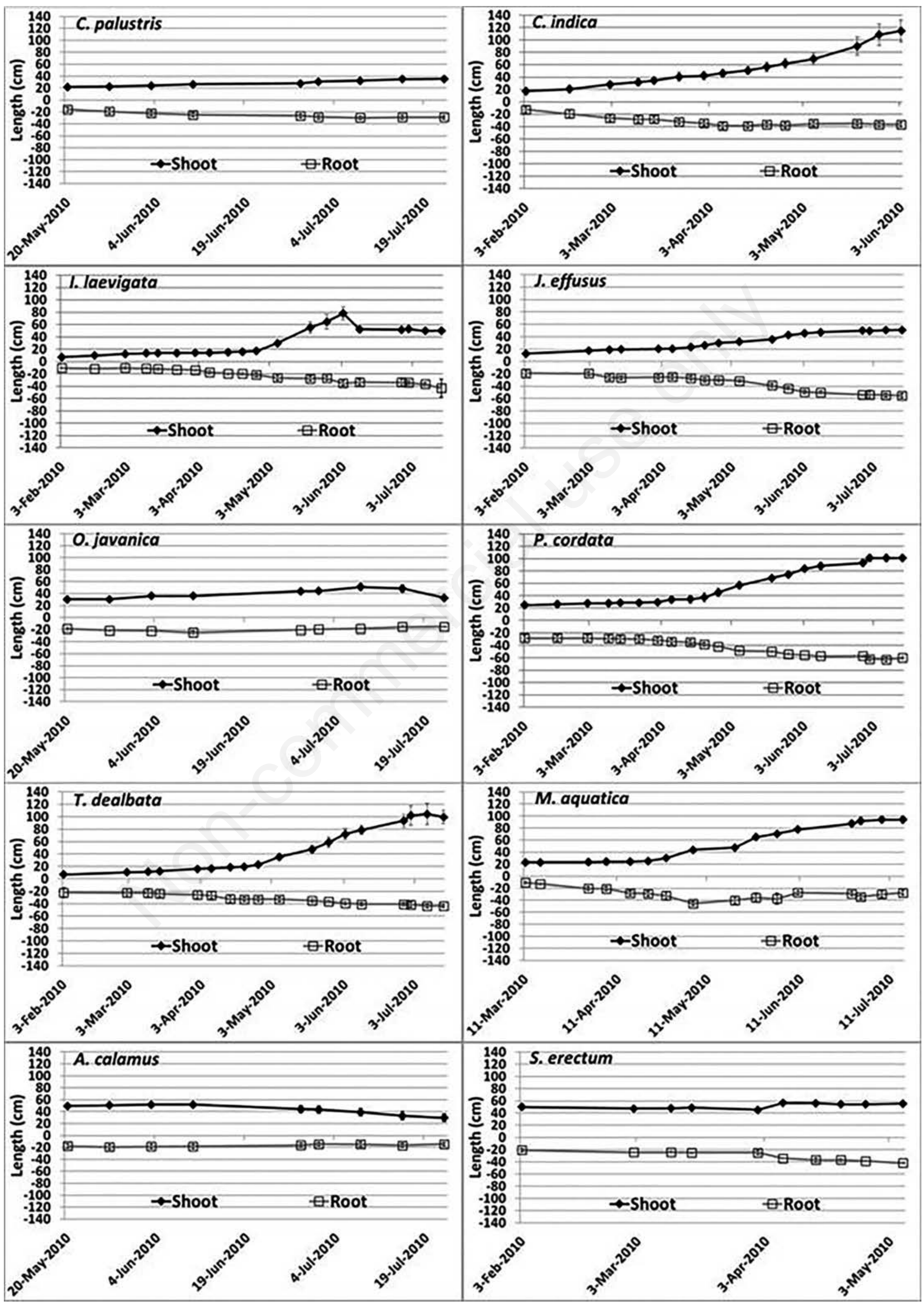

Figure 5. Evolution of the biometric parameters (shoot height, cm and root length, cm) over the growing season for the studied species (average value±standard error).

respect to the other species (at the end of May) (Figure 5). For these species, the sprouting phase was not monitored as they were installed on the floating mats in early spring using plants from a specialist nursery instead of rhizomes. The biometric characteristics of *O. javanica* and *C. plaustris* remained almost constant over the entire monitoring period with average shoot height of 39.3±7.8 cm and 28.5±1.7 cm, respectively and average root length of 19.7±1.0 cm and 24.9±1.6 cm, respectively (Figure 5).

A. calamus and *S. erectum*, maintained almost constant shoot height and root length from the beginning of the monitoring period to late spring (May 5th and June 10th for *S. erectum* and *A. calamus*, respectively), they then progressively reduced, reaching the senescence phase before all other species (Figure 5).

Significant differences (ANOVA, P<0.01) in the maximum values of both shoot and root length were detected among species due to their different morphology and adaptability to grow in hydroponic conditions (Figure 6). *C. indica P. cordata*, *T. dealbata* and *M. aquatica* showed the significantly highest (ANOVA, P<0.01) maximum shoot height (average value 103.6±4.2 cm) (Figure 5). On the contrary, *C. palustris* and *J. effusus* reached the significantly lowest (ANOVA, P<0.01) maximum shoot height with average values of 35.2±2.7 cm and 51.0±2.7 cm, respectively. The maximum shoot height of *J. effusus* was in line with the average values obtained in two FTWs built with Beemat® (43.4 cm) and BioHaven® (48.7 cm) (Lynch *et al*., 2015), whereas it was more than twice lower than the maximum value recorded for *Juncus edgeriae* by Tanner and Headley (2011) (130±13 cm).

P. cordata shoot height was greater than that reported by Wang *et al*. (2015), treating urban wastewater, with an average value of 43 cm. Shoot height of *A. calamus* matched the values reported by Chang *et al*. (2010) (45.2 cm) and Li and Guo (2017) (more than 55 cm under 9.63 mg L^{-1} of total nitrogen). The maximum shoot height of *O. javanica* measured in this study was about 2.6 and 2.9 times those obtained in FTWs treating polluted river water and domestic wastewater (Duan *et al*., 2016).

P. cordata and *J. effusus* showed the significantly highest (ANOVA, P<0.01) maximum root length (62.0±3.1 cm and 51.0±3.6 cm, respectively), whereas *A. calamus* and *O. javanica* had the significantly lowest (ANOVA, P<0.01) ones (19.5±3.8 cm and 24.8±2.3 cm, respectively). Shorter roots than those recorded in the current study were reported for *J. effusus* (37.4-39.1 cm) (Lynch *et al*., 2015) and *J. maritimus* (36-38 cm) (Pavan *et al*., 2015). On the contrary, longer roots were obtained in hydroponic conditions by Tanner and Headley (2011) (maximum length for *J. edgeriae* of 87±12 cm) and White and Cousins (2013) (more than 60 cm for *J. effusus*).

A. calamus root length was in line with values reported by Chang *et al*. 2010 (15.4 cm) and Lai *et al*. (2011) (23.0 cm), whereas *C. indica* and *O. javanica* root lengths were respectively 3.4 and 1.7 times those reported by Lai *et al*. (2011) in a pilot scale plant.

For the majority of studied species, shoot height was positively correlated with root length over the entire monitoring period (Table 3), suggesting a simultaneous elongation of all plant organs. Only *S. erectum* and *O. javanica* did not show any significant correlation between these parameters. In addition, the relationship existing between the two parameters followed a species-specific trend during the first part of the vegetative season (sprouting), with a positive linear regression for *C. indica*, *P. cordata* and *T. dealbata* and an insignificant relationship for the other studied species (Table 3). In the next phase, from the beginning of shoot elongation to blooming phase, all studied species behaved similarly, contemporarily increasing shoot height and root expansion in the water column (Table 3). Instead, at flowering-fruit development, it was not possible to find a significant regression between shoot height and root length for the majority of species (Table 3). Indeed, during

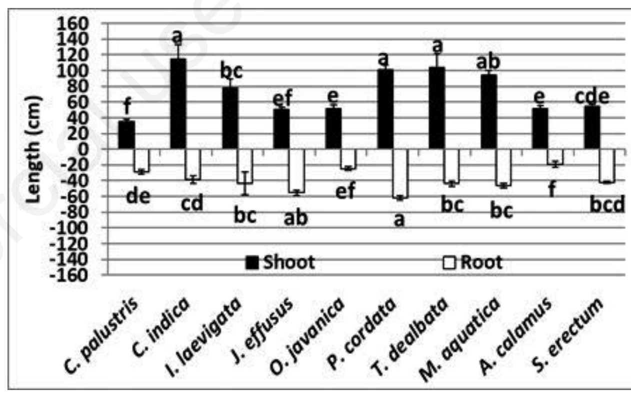

Figure 6. Maximum biometric parameters (shoot height, cm and root length, cm) (average value±standard error) for the studied species. Different letters within the same parameter indicate significant differences among the species according to Fischer Least Significant Difference, LSD test, P<0.05.

Table 3. Linear regression analysis between root length (cm, dependent variable, y) and shoot height (cm, independent variable, x) for the different phenological phases of used ornamental species.

Species	Sprouting phase (February 3rd-March 16th)		Shoot elongation (March 24th-May 27th)		Flowering-fruit development (June 3rd-July 30th)		Entire cycle	
	Equation	R	Equation	R	Equation	R	Equation	R
C. palustris	-	-	y=-0.9749+0.918x	+0.48 ***	y=21.937+0.215x	+0.19 ns	y=0.608+0.662x	+0.50 ***
C. indica	y=5.424+0.665x	+0.71 **	y=27.356+0.171	+0.35 *	y=22.985+0.118x	+0.55 ns	y=20.608+0.225x	+0.53 ***
I. laevigata	y=8.986+0.203x	+0.37 *	y=14.407+0.254x	+0.13 ***	y=108.64-0.697x	-0.13 ns	y=12.774+0.590x	+0.71 ***
J. effusus	y=24.610+0.009x	+0.01 ns	y=12.151+0.700x	+0.69 ***	y=34.599+0.337x	+0.19 ns	y=10.878+0.790x	+0.80 **
O. javanica	-	-	y=23.033-0.05x	+0.07 ns	y=18.492-0.017x	-0.070 ns	y=23.684-0.093x	-0.238 ns
P. cordata	y=15.460+0.511x	+0.51 ***	y=22.248+0.398x	+0.76 ***	y=53.498+0.455x	+0.13 ns	y=21.331+0.384x	+0.83 ***
T. dealbata	y=22.680+0.151x	+0.03 ns	y=22.876+0.247x	+0.43 **	y=43.844-0.280x	-0.11 ns	y=25.032+0.157x	+0.492 ***
M. aquatica	y=22.686-0.052x	+0.05 ns	y=30.034+0.147x	+0.20 *	y=22.206+0.130x	+0.14 ns	y=22.817+0.105x	+0.21 *
A. calamus	-	-	y=-3.293+0.411x	+0.36 **	y=5.049+0.276x	+0.537 ***	y=4.751+0.269x	+0.469 ***
S. erectum	y=23.935-0.002x	+0.71 ns	y=87.571-0.956x	-0.66 ns	-	-	y=12.104+0.309x	+0.27 ns

-: not available; ns: not significant; * significant, P<0.05; **: significant, P<0.01; ***: significant, P<0.001.

this phenological phase (June-July), plant root systems continued their expansion through the water column, whereas shoot height remained almost constant since the maximum values were reached at the end of June, in correspondence with blooming.

Different root length/shoot height ratio values were found among species (Figure 7). In particular, *T. dealbata*, *J. effusus* and *I. laevigata* (1.23±0.11, 1.21±0.06, 1.19±0.09, respectively) showed the highest values on the average of the vegetative cycle, whereas *S. erectum*, *O. javanica* and *A. calamus* exhibited the lowest ones (0.54±0.03, 0.56±0.01, 0.41±0.02, respectively). Focusing attention on the different vegetative season phases, *C. indica*, *P. cordata*, *T. dealbata*, *M. aquatica* and *J. effusus* progressively reduced their root length/shoot height ratio from the beginning of the growing season (sprouting) to the last phenological phases (Figure 7). The behavior of all other species was different, since their root length/shoot height ratio values were maintained almost constant throughout the monitoring period (Figure 7).

Biomass production

The studied species gave significantly different (ANOVA, P<0.001) biomass production at harvest (Table 4), reflecting the same statistical trend as that observed for shoot height, as testified by the strictly positive correlation existing between plant above-mat biomass production (y) and shoot height (x): $y=15.19\ x - 606.94$, $R^2=0.75$, $P<0.05$. In particular, *M. aquatica* and *C. indica* showed significantly higher (ANOVA, P<0.001) above-mat dry biomass productions than those obtained for *O. javanica*, *J. effusus* and *C. palustris*, which showed no significant differences (Table 4). *M. aquatica* gave a much higher production compared to an experiment carried out in mesocosms on LECA substrate (Tamiazzo *et al*., 2015) under similar climatic conditions and was one of the most productive species in a bioretention pond where Tech-IA® floating mats were installed (Zanin *et al*., 2018). *C. indica* above-mat production obtained in this study was higher than that reported by Zhang *et al*. (2007) (0.5-1.0 kg m^{-2}) in a pilot scale vertical flow system fed with a simulated nutrient solution, whereas it was in line with results obtained by Zhao *et al*. (2012) in an FTW treating eutrophic river water (1000-1500 g m^{-2}). Higher above-mat biomass productions than ours were obtained in a pilot FTW treating eutrophic wastewater (2.37-2.43 kg m^{-2}), with equal partitioning between stems and leaves (Zhang *et al*., 2016).

T. dealbata and *P. cordata* biomass productions were in disagreement with the results found in the scientific literature, since productions of 1989.0 g plant^{-1} (*T. dealbata*) and 10.4-71.8 g plant^{-1} (*P. cordata*) were reported by Ge *et al*. (2016), Wang *et al*. (2014) and Winston *et al*. (2013), respectively. In the present study, *J. effusus* above-mat production was lower than those harvested by Borin and Salvato (2012) in mesocosm gravel tanks (3210.0 and 5271.0 g m^{-2}) and by Winston *et al*. (2013) in an FTW (66.2-106.3 g plant^{-1}) whereas it was higher than those obtained in a hydroponic culture of stormwater run-off (on average 142.9-188.4 g m^{-2}) (Lynch *et al*., 2015) and diluted digestate liquid fraction (median value 172.0 g m^{-2}) (Pavan *et al*., 2015). *S. erectum* and *A. calamus* maximum shoot heights and root lengths were measured until late spring (June), whereas their biomass production was not harvested since they did not survive until the harvesting period (July). The negative adaptability of *S. erectum* contrasted with expectations, since Ennabili *et al*. (1998) assessed a good growth of the species (1293 g m^{-2} and 718 g m^{-2} of above- and below-ground biomass, respectively) in sandy-clay soil typical of coastal wetlands.

N concentration and uptake

Despite statistically similar above-mat nitrogen percentage concentrations among species (Table 4), significant differences (ANOVA, P<0.001) in their above-mat nitrogen uptakes were detected, mainly depending on above-mat biomass production, as confirmed by Zhu *et al*. (2011). The similar above-mat nitrogen percentage concentration among the species is probably justified because they were cultivated in the same nutrient solution.

The above-mat N percentage concentration values observed in this study were lower than those determined in similar experimental conditions for *C. indica* (1.65-2.75%) (Zhang *et al*., 2016) but were in line with those reported for *J. effusus* (0.83%) (Lynch *et al*., 2015), *J. edgeriae* (1.2%), *C. virgata* (1.1%), *C. ustulatus* (1.2%) and *S. tabernaemontani* (1.4%) (Tanner and Headley, 2011). Double N concentrations than ours were reported for *C. indica* and *P. cordata* on a floating island treating eutrophic water (Zhao *et al*., 2012).

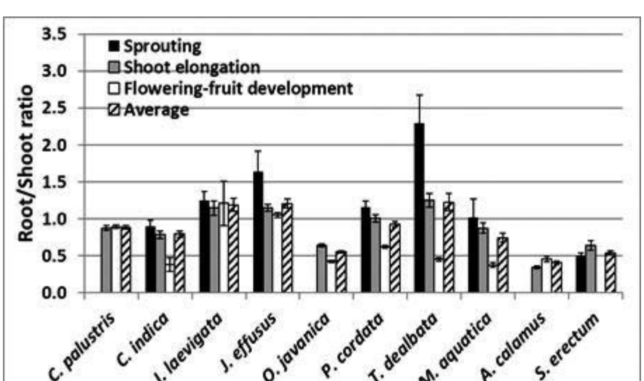

Figure 7. Evolution of the root length/shoot height ratio during the vegetative cycle (average value±standard error).

Table 4. Above-mat biomass production (average value±standard error, g m^{-2}), nitrogen percentage concentration (average value ±standard error, %), nitrogen uptake (average value ±standard error, g m^{-2}) and survival rate (%) of species in the study. Different letters within the same parameter indicate significant differences among the species according to Fischer Least Significant Difference, LSD test (P<0.001).

Species	Above-mat biomass (g m^{-2})	Nitrogen concentration (%)	Nitrogen uptake (g m^{-2})	Survivability (%)
C. palustris	33.5±6.2^{c}	1.02±0.006	0.3±0.06^{c}	100
C. indica	1638.9±359.8^{b}	0.98±0.046	15.1±2.54^{b}	100
I. laevigata	104.1±4.6^{c}	1.02±0.004	1.1±0.04^{c}	100
J. effusus	88.8±22.1^{c}	1.01±0.012	0.9±0.23^{c}	66.7
O. javanica	102.3±3.4^{c}	1.01±0.012	1.0±0.04^{c}	100
P. cordata	483.4±132.1^{c}	1.02±0.010	5.0±1.39^{c}	100
T. dealbata	566.1±200.1^{c}	1.00±0.007	5.7±2.00^{c}	100
M. aquatica	3162.1±512.0^{a}	1.02±0.003	32.1±5.29^{a}	50
A. calamus	-	-	-	0
S. erectum	-	-	-	0
Z. aetiopica	-	-	-	0
Sig.	***	ns	***	-

-: not available, ns: not significant, ***: significant at P<0.001.

M. aquatica and *C. indica* showed significantly higher (ANOVA, P<0.01) above-mat nitrogen uptakes than those of all the other species, which in turn did not significantly differ (Table 4). *C. indica* above-mat N uptake was in line with results reported for *C. flaccida* (16.1 g N m^{-2}) by White and Cousins (2013). Despite White and Cousins (2013) reporting good N uptake for *J. effusus* (28.5 g m^{-2}), a contrasting behavior was observed in this study since the average N uptake was 0.9 g m^{-2}.

The above-mat N uptake through plants aerial biomass harvesting plays an important role in wastewater treatment, because it allows a definitive removal of the element from the treatment site.

At this purpose, the harvesting of vegetation in a FTW should be done before plant complete senescence to limit the translocation of nutrients from above-mat to below-mat tissues, therefore maximizing nutrients removal from wastewater. In addition, plant biomass should be cut almost 10 cm above the floating mat to guarantee an enough coverage and protection of the blow-mat tissues against cold icy winter, therefore allowing an excellent vegetative regrowth.

Survival rates

All plants of *C. indica*, *I. laevigata*, *O. javanica, P. cordata, C. palustris* and *T. dealbata* survived for the entire growing season (Table 4). These findings agree with Wu *et al*. (2011), Zhu *et al*. (2011) and Ge *et al*. (2016) who observed high survival rates for *T. dealbata*, *O. javanica* and *C. indica*, respectively. Also, Xu *et al*. (2017) reported an interesting adaptability of *T. dealbata* under hydroponic conditions, with survival rates higher than 98%. The high survival of *C. indica* was in opposition to that obtained in a pilot scale experiment where the species was cultivated in open-air conditions, and managed with high water and nutrient inputs (Barco *et al*., 2018; Maucieri *et al*., 2018) because it was not able to tolerate winter cold. The high survival exhibited by *C. palustris* was previously confirmed by Pappalardo *et al*. (2017) in an FTW treating agricultural run-off (73% survival rate). The excellent survival of *Iris* was previously confirmed by Barco and Borin (2017), Pavan *et al*. (2015) and Mietto *et al*. (2013). The good performances recorded in the current study for *P. cordata* disagreed with results obtained in a stormwater retention pond where the species mortality varied between 68% and 89% (Tharp *et al*., 2019).

Table 5. Suitability index calculated for all studied species.

Species	Survival rate	Above-mat biomass	Nitrogen uptake	Root length	Root/Shoot ratio	Suitability index
C. palustris	2	1	1	2	3	14
C. indica	2	2	2	2	2	16
I. laevigata	2	1	1	3	3	16
J. effusus	1	1	1	3	3	8
O. javanica	2	1	1	2	2	12
P. cordata	2	1	1	3	3	16
T. dealbata	2	1	1	3	3	16
M. aquatica	1	3	3	3	2	11
A. calamus	0	-	-	1	1	0
S. erectum	0	-	-	3	2	0
Z. aetiopica	0	-	-	-	-	0

Negative performances were obtained for *A. calamus*, *Z. aetiopica* and *S. erectum* which did not survive the growing season. The low adaptability of *S. erectum* to hydroponic conditions was also observed by Pappalardo *et al*. (2017) with only 8% of plants surviving after the first growing season.

Suitability index

As mentioned earlier, the SI was adopted to select the most promising species to install in FTWs, basing on different characteristics. Considering this approach, *C. indica*, *P. cordata*, *T. dealbata* and *I. laevigata* were the most suitable species to install in an FTW (SI was 16) thanks to their high survivability, high biomass production as well as nitrogen uptake and a comparable extension of aerial and root tissues (Table 5). Despite *J. effusus* and *C. palustris* showed a balanced development between aerial and root tissues, their above-mat biomass production and consequent nitrogen uptake were lower than those obtained for the previous species, therefore justifying intermediate SI values (from 8 to 14) (Table 5). An intermediate SI was also obtained for *O. javanica*, whose installation in FTW should be limited due to the higher extension of aerial than root tissues therefore indicating probable overturning of floating vegetated barriers under extreme meteorological events. The choice of *Z. aetiopica*, *S. erecutum* and *A. calamus* should be avoided due to a scarce aptitude to survive under hydroponic conditions.

Conclusions

The study aimed to report the growth performances of eleven un-floating ornamental species installed in a pilot scale FTW and fertilized with a synthetic nutrient solution. In addition, it would give practical advice for the installation of FTWs, especially in urban water bodies where the necessity to select plant species characterized by contemporaneous adaptability to survive under high pollutants load and esthetic-ornamental values represents a real difficulty to be overcome. For this purpose, *C. indica*, *P. cordata* and *T. dealbata* appeared to be the most suitable species, thanks to their vigor during the vegetative season, the highest above-mat biomass produced as well as nitrogen uptake, excellent survivability and balanced growth between aerial and root tissues. Excellent growth was also shown by *M. aquatica*, even though it did not completely survive like the previous species. The selection of *O. javanica* should be avoided due to the higher development of above-mat rather than below-mat tissues with a consequent probable overturning of the floating barriers under extreme meteorological events.

The negative performances exhibited by *Z. aetiopica, S. erectum* and *A. calamus* in terms of survival does not suggest their installation in hydroponic conditions.

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