ARTÍCULOS

Botanica Complutensis
ISSN-e: 1988-2874

https://dx.doi.org/10.5209/bocm.80494

EDICIONES COMPLUTENSE

Functional aspects of *Pistia stratiotes*, an invasive plant of lentic freshwater habitats of Al Jawahir Wadi (Fez, Morocco)

Chaimae Chadli[1], Mohamed Libiad[2], Abdelmajid Khabbach[3], Rabia Bouslamti[4], Abdeslam Ennabili[5]

Abstract.
Excessive growth of invasive alien aquatic plants threatens local ecosystems and has both ecological and economic impacts. This work highlights morphological and functional aspects of *Pistia stratiotes* L., first reported in Fez in 2012. The total photosynthetic area of a *Pistia* plant is highly correlated (R^2=0.70) to the product of the length and maximum width of the outer leaf. The total biomass of *Pistia* was highly related (R^2=0.71) to plant size and averaged 67.54±26.35 g dry weight·m^{-2}. Its peak does not necessarily co-occur with flowering and/or high production of stolons. The total nitrogen and phosphorus mineralomasses correspond to 11.46±4.55 kg N·ha^{-1} and 0.83±0.33 kg P·ha^{-1}. The biomass and mineralomasses of *Pistia*, estimated under these invasive conditions, ranks it among the least productive Moroccan wetland plants.
Keywords: Water lettuce; Morocco; leaf index; biomass; nitrogen and phosphorus accumulation.

[es] Aspectos funcionales de Pistia stratiotes, una planta invasora de los hábitats lénticos de agua dulce del rio Al Jawahir (Fez, Marruecos)

Resumen. El crecimiento excesivo de plantas acuáticas exóticas invasoras amenaza los ecosistemas locales y tiene impactos tanto ecológicos como económicos. Este trabajo destaca aspectos morfológicos y funcionales de *Pistia stratiotes* L., reportada por primera vez en Fez en 2012. La superficie fotosintética total de una planta de *Pistia* está altamente correlacionada (R^2=0,70) con el producto de la longitud y la anchura máxima de la hoja externa. La biomasa total de Pistia estaba altamente relacionada (R^2=0,71) con el tamaño de la planta con un promedio de 67,54±26,35 g peso seco·m^{-2}. Su pico no coincide necesariamente con la floración y/o la alta producción de estolones. Las mineralomasas de nitrógeno y fósforo totales suponen 11,46±4,55 kg N·ha^{-1} y 0,83±0,33 kg P·ha-1. La biomasa y las mineralomasas de *Pistia*, estimadas en estas condiciones de invasión, la sitúan entre las plantas menos productivas de los humedales marroquíes.
Palabras clave: Lechuga de agua; Marruecos; índice foliar; biomasa; acumulación de nitrógeno y fósforo.

1. Introduction

Invasive exotic plants rely on rapid and extensive colonization dynamics in ecosystems outside their natural range (Matrat et al. 2012). Invasion success by these species generally depends on the interaction of local habitat characteristics and biotic resistance provided by native vegetation, although disturbed systems are generally more susceptible to invasion due to, inter alia, increased fluctuations in resource availability (Hussner et al. 2017). Invasive exotic aquatic plants threaten ecosystems because of their excessive growth and both ecological and economic impacts. Prevention of their introduction is considered the most cost-effective management option; otherwise, early detection and rapid response increase the likelihood of their eradication and can minimize the management costs incurred (Hussner et al. 2017). Ecologically, they severely alter the characteristics of native ecosystems, including the

[1] LMPCE Laboratory, Superior School of Technology, Sidi Mohamed Ben Abdellah University, Fez, Morocco.
E-mails: chaimaechadli98@gmail.com
[2] LESCB laboratory, CNRST Labeled Research Unit Nº18, Faculty of Sciences, Abdelmalek Essaâdi University, Tetouan, Morocco.
E-mail: libiad001@gmail.com
ORCID: https://orcid.org/0000-0002-0731-8914
[3] SNAMOPEQ Laboratory, Faculty of Sciences, Sidi Mohamed Ben Abdellah University, Fez, Morocco.
E-mail: khamajid@hotmail.com
ORCID: https://orcid.org/0000-0002-6779-9078
[4] LMPCE Laboratory, Superior School of Technology, Sidi Mohamed Ben Abdellah University, Fez, Morocco.
E-mail: rabia.bouslamti@usmba.ac.ma
[5] LMPCE Laboratory, Superior School of Technology, Sidi Mohamed Ben Abdellah University, Fez, Morocco.
E-mail: abdeslam.ennabili@usmba.ac.ma
ORCID: https://orcid.org/0000-0003-0133-1920
Corresponding author.

components of living communities, nutrient cycling, hydrology, and energy balances, and can greatly contribute to the eutrophication of these aquatic systems (Villamagna & Murphy 2010; Santos et al. 2011; Stiers et al. 2011; Nouga Bissoue et al. 2017).

Wetlands currently provide habitat for about 36% of the Moroccan vascular flora, with specific, facultative or opportunistic affinities (Ennabili et al. 2021). Within the 16 introduced plant taxa specific to Moroccan wetlands, five are naturalized, two naturalized or invasive, depending to the authors, and only one invasive, *Pistia stratiotes* L. (Khabbach et al. 2020). Reported in Fez for the first time in 2012, this species is increasingly spreading along Al Jawahir Wadi despite measures implemented to limit its spread. Hydrological, urban and pollution hazards downstream of this river would be among the factors temporarily limiting its extension outside this sub-watershed. Ongoing decontamination efforts in this river and the exceptional ability of this species to spread would represent a real threat to local water bodies (Khabbach et al. 2019).

The local introduction of *P. stratiotes*, under the climatic warming detected in the Fez Region since the eighties (Driouech 2010), could be related to its use in phytoremediation or secondarily as an ornamental plant. Several applied research studies recommend the use of this invasive species in phytoremediation by virtue of its water pollution tolerance, nutrient and metal retention capacities (Lu et al. 2010, 2011; Galal & Farahat 2015; Prajapati et al. 2012). However, there are native aquatic (Sasmaz et al. 2015; Ennabili et al. 2019), semi-aquatic (Bello et al. 2018; Ennabili & Radoux 2020), or riparian (Cristaldi et al. 2020; Ennabili & Radoux 2021) plant species that all have demonstrated these benefits, and consequently, this should not be a reason for its introduction for this purpose either. Moreover, the natural aquatic vegetation of Morocco also hosts species with ornamental potential, namely *Nymphaeaceae*, *Hydrocharitaceae*, *Haloragaceae*, *Alismataceae*, *Crassulaceae*, etc. (Khabbach et al. 2020).

Pistia stratiotes can survive drying and re-infest ephemeral waters due to seed survival and germination. As excessive growing floating plants, it can significantly alter aquatic ecosystems by impacting their biodiversity negatively, inhibit photosynthesis in the water beneath the plant mat, degrade drinking water quality, increase water losses through evapotranspiration, interfere with various water structures, reduce access to recreation, and promote the transmission of waterborne diseases (EPPO 2017). The development of environmental and socio-economic measures to limit the expansion of this species is therefore a necessity. Khabbach et al. (2019) have reported the distribution of *P. stratiotes* in and around the watershed of Al Jawahir Wadi according to socio-ecological and planning hazards, and also characterized it morphologically. This work aims to assess some functional aspects of this plant species in full invasion of Wadi Al Jawahir, in order to contribute in identifying useful elements for the fight against its spread.

2. Material and Methods

2.1. Characterization of the study area

The study site is located in Al Jawahir Wadi, Fez (Fig. 1a; N 34°02'48" W, 5°03'44", 374 m), one of the previous survey sites conducted by Khabbach et al. (2019). The vegetation in this location consists of a succession of plant groups composed of *Pistia stratiotes*, *Typha angustifolia* L., and *Phragmites australis* (Cav.) Trin. ex Steud, with companion species typical of wetlands such as *Lemna minor* L., *Ceratophyllum demersum* L., *Nasturtium officinale* R. Br., *Mentha suaveolens* Ehrh., *Verbena officinalis* L., *Rumex* spp., *Plantago major* L., *Cyperus longus* L., *Polypogon monspeliensis* (L.) Desf., etc., or species of disturbed sites at the riverbank such as *Symphyotrichum squamatum* (Spreng.) G.L. Nesom, *Dittrichia viscosa* (L.) Greuter, *Hordeum murinum* L., etc. (Fig. 1b).

Sections of the river covered by *Pistia* and reedbeds along the edge experience apparently tolerated activities related to waterfowl, particularly common moorhens (*Gallinula chloropus* L., 1758) and coots (*Fulica atra* L., 1758), and freshwater fishing. Moreover, control techniques against *Pistia* were applied at the beginning of the invasion of Al Jawahir Wadi by the Plant Protection Service, namely manual uprooting, the deposit of narrow mesh screens across the stream, and releases of the insect *Neohydronomus affinis* Hustache (1926), a biological control agent of this plant species (SPV 2019). As a result, *Pistia* develops an adaptive strategy by developing reproductive cycles temporally out of phase, both in water and on the mud at the river's edge.

Three instantaneous water samples were taken from the right, middle and left bank sides of the river. In situ measurement of physic-chemical parameters of the water was performed by Hanna HI98194 multi-parameter probe, namely Hydrogen Potential (pH), Temperature (T), Electrical conductivity (Ec), Dissolved Oxygen (DO), Total Dissolved Solids (TDS), and Practical Salinity Unit (PSU). In laboratory, the weight of Total Suspended Solids (TSS) was obtained by differentiating the weights of previously dried glass fiber filters before and after vacuum filtration of a volume of the water sample. The Chemical Oxygen Demand (COD) was determined by chemical oxidation with potassium dichromate at 150°C for 2 h in acidic medium, using a HI839800 thermoreactor. The residual dichromate concentration was measured at 610 nm using the HI83224 photometer, developed by the Hanna Company.

The colorimetric analysis techniques proposed by this firm were also used for the measurement of other parameters, namely Total Nitrogen (TN) by digestion in the presence of persulfate, Nitrates ($N-NO_3$) using chromotropic acid, and Total Phosphorus (TP) by vanadomolybdophosphoric acid. The photometric measurement at 420 nm for the nitrogen and phosphorus parameters was monitored. Total Coliforms (TC) and Fecal Coliforms (FC) were enumerated by the Most Probable Number (MPN) method using the BLBVB culture medium at 40 $g \cdot l^{-1}$. The volume of 9 ml was distributed in each tube, and then all tubes were autoclaved for 20 min. After inoculation, the tubes were incubated for 24 h at 37°C for TC and 44.5°C for FC.

Table 1 presents all the physic-chemical and microbiological parameters of the water measured at the optimum development of *Pistia*. Except for TSS and COD, relatively high mainly due to debris of *Lemna* and *Ceratophyllum* species, competitors with *Pistia*, the quality of the river water was not of concern at this time of year. But monitoring of water quality throughout the year and macrophyte stands during the growing season classify this station as being in an advanced stage of degradation, i.e., medium to poor quality (Khabbach et al. 2019; Kanga et al. 2021).

2.2. Plant measurements and analysis

A hundred *Pistia* plants were randomly collected in the mid spring of 2021 from the study area, and transferred to the laboratory for morphological characterization based on the criteria given in Fig. 1c. Biometric measurements described by Khabbach et al. (2019) such as plant size, height and diameter of the leaf rosette, maximum root length, number and length of stolons per plant, number of outer leaves, and length and width of outer leaves and their number per plant were recorded. Such parameters were completed for the middle and inner leaves of the main rosette and those of the daughter rosette. Stolon thickness and inflorescence number were also noted. The wet leaves, roots and stolons were washed, drained and weighted separately for each plant.

All these measurements helped to approach functional characteristics of *Pistia*, namely the water surface occupied by this plant, and its density, leaf area, photosynthetic area, biomass, and/or nitrogen and phosphorus mineralomasses. Considering the total coverage of the water surface by *Pistia*, its density (D, $plants \cdot m^{-2}$) was approximated according to Equation 1:

$$D = {}^{4 \cdot 10^4}/_{\pi \cdot LGD^2} \quad (1)$$

where LGD is leaf rosette-global diameter (cm).

In addition, the leaf area (LA, cm^2) was estimated indirectly using homogeneous density fortified paper cut, dried, and weighed, using Equation 2:

$$LA = {}^{w}/_{d} \quad (2)$$

where w is the weight of the cut paper in the shape of the plant leaf (g), and d the density of the square cut paper ($g \cdot cm^{-2}$). The photosynthetic area is the sum of the green areas of the plant, i.e. leaves of the principal rosette and daughter ones (TLA), and stolons. The leaf area index (LAI) is the ratio of the photosynthetic area to the water surface occupied by the plant.

To determine dry weight, each plant part was dried at 75°C for 3 days to constant weight. Destructive or direct methods to estimate the biomass of *Pistia* were not used in this study because the sites infested by this plant along Al Jawahir Wadi are mostly perturbed; the preserved sites are relatively insignificant in terms of area (Khabbach et al. 2019). The biomass (B, $g \cdot m^{-2}$) of *Pistia* was in fact estimated indirectly by multiplying the dry weight of the plant (dw, g) by its density ($plants \cdot m^{-2}$). To estimate the nitrogen and phosphorus contents of the *Pistia* biomass, the roots and the leaf part were ground separately using a 0.5 mm perforated trapezoidal sieve and analyzed according to the Nessler method (Ennabili et al. 2019).

2.3. Statistical analysis

The 100 plants collected included 35 with stolons and 19 with inflorescences. Two one-way analyses of variance were performed for all measured parameters with a normal distribution by using Statistica, V.5 software: one comparing plants with and without stolons, and the other comparing plants with and without inflorescences. Regression analyses, without any regard to the presence or absence of stolons and/or inflorescences, and calculation of means and standard deviations were performed using Microsoft Excel.

3. Results

3.1. Leaf area

The leaf area is the key part of photosynthetic activity, which is used as a reference to characterize the biomass production of plants. The leaf area, measured indirectly, averages 28.91±12.01 and 32.81±14.73 cm^2 for the outer and middle leaves of the plant rosette, respectively. It is most correlated with the maximum width of the outer leaf and the product of the length and maximum width of the middle leaves (Table 2). The total leaf area (TLA) of a *Pistia* plant from Al Jawahir Wadi is highly correlated (R^2=0.70) with the product of the length and maximum width (L·W) of the outer leaf (Fig. 2a) according to Equation 3:

$$TLA = 0.017 \cdot (L \cdot W)^2 + 2.582 \cdot L \cdot W + 20.22 \quad (3)$$

The photosynthetic area of *Pistia* is estimated at 192.04±83.73 cm^2, which is distributed over 2.95±0.62 cm^2 middle leaves (52.92%), 2.69±1.01 cm^2 outer leaves of the rosette (41.55%), 2.47±1.33 cm^2 of stolons (3.89%), and 1.23±1.17 cm^2 outer leaves of daughter rosettes (1.64%). The outer leaves of the rosette (1.9±0.77 cm^2) and the middle (0.7±0.65 cm^2) and inner (0.33±0.48 cm^2) leaves of the daughter rosettes are too small with incomplete blade development. The comparison of the area of the green part of plant according to the presence and absence of stolons (F=1.8944, p=0.1732) and/or inflorescences (F=2.9779, p=0.093) does not show significant differences (Fig. 2b).

The leaf area index (LAI) is estimated by 1.01±0.37, i.e. an approximate total interception of the light arriving on the colonized water body. *Pistia* plants did not show significant differences in LAI with respect to the presence and absence of inflorescences (F=1.7262, p=0.1972). While plants with stolons show a significantly lower LAI, allowing partial light penetration into the water, in comparison to those without stolons (F=13.644, p=0.0004); Fig. 2b.

3.2. Plant biomass

With an average density of 60.69±29.35 plants·m^{-2}, the total biomass (TB) of *Pistia* from Al Jawahir Wadi is highly related (R^2=0.71) to plant size (PS) by the function in Equation 4 (Fig. 3a):

$$TB = PS^{1.262} \quad (4)$$

The average plant size of *Pistia* is 26.95±8.34 cm and corresponds on average to a total biomass of 67.54±26.35 g dw·m^{-2}. The green part of the plant, above the water surface, produces 4.4 times more biomass than the root part, resulting in leaves (including inflorescences), stoloniferous and root biomasses of 53.81±20.52, 2.44±2.64, and 12.79±8.49 g dw·m^{-2}, respectively. The specific photosynthetic area, as the ratio of photosynthetic area to dry weight of the leafy part of the plant above the water surface, is estimated by 17.67 m^2·kg^{-1}, equivalent to a specific weight of 56.6 g·m^{-2}. In the upper 40 cm of water column, the density of the main roots is about 11.51 m of root system m^{-2} of water surface, representing a specific root biomass of 69.66 g dw·m^{-3}. This is particularly advantageous for phytoremediation in natural distribution areas of *Pistia* and where it does not present any invasion hazard for water surfaces.

The comparison of biomass with the presence and absence of stolons (F=0.856, p=0.3581) and/or inflorescences (F=0.2252, p=0.638) shows no significant differences (Fig. 3b), although the plant density of plants with stolons (45.76±18.77 plants·m^{-2}) is clearly lower than that of plants without stolons (76.1±31.36 plants·m^{-2}, F= 24.109, p=6.0E-06). The biomass of *Pistia* can be estimated locally based on a simple measurement of the size of a representative plant. Peak biomass does not necessarily coincide with flowering and/or high stolon production. Mechanical control intervention could take place before the flowering stage whilst achieving significant biomass and limiting the production of seeds, which have a high germination potential.

3.3. N and P accumulation

The nitrogen and phosphorus contents of *Pistia* are roughly 17 g N·kg^{-1} and 1.3 g P·kg^{-1} for the leafy part and 19 g·kg^{-1} N and 1.1 g P·kg^{-1} for the root one, corresponding to total nitrogen and phosphorus mineralomasses of 11.46±4.55 kg N·ha^{-1} and 0.83±0.33 kg P·ha^{-1}. The above-water part of the plant accumulates about 4 times more nitrogen and 5 times more phosphorus compared to the root part below the surface water, i.e. 9.08±3.49 kg N and 0.69±0.27 kg P·ha^{-1} against 2.38±1.6 kg N and 0.14±0.09 kg P·ha^{-1} in the same order. The comparison of nitrogen and phosphorus mineralomass according to the presence and absence of stolons (F=0.4258, p=0.5163 - N; F=0.3399, p= 0.5618 - P) and/or inflorescences (F=0.2189, p=0.6427 - N; F=0.2619, p=0.612 - P) showed no significant differences. Export of *Pistia* biomass pre-bloom would apparently not have a significant effect on its N and P accumulation.

4. Discussion

4.1. Plant development status

Pistia plants invading Al Jawahir Wadi were characterized for the first time by Khabbach et al. (2019). The perceived extension of the dry period in the study area, and the disturbance of the lentic habitat due to various hazards, including agricultural and urban pollution, are responsible for the water characteristics recorded in continental, subtropical, tropical and desert climates, viz. pH, dissolved oxygen, electrical conductivity, total suspended solids and/or phosphorus (Šajna et al. 2007, Eid 2017, Galal et al. 2019, Živković et al. 2019).

During full vegetation, *Pistia* develops more than one developing cycle so that pre-flowered, flowering, fruiting, and/or senescing individuals co-occur in different proportions. Occasionally, it is rooted in mud following intermittent flooding (Khabbach et al. 2019). The various pheno-phases of this plant are then displayed along the warm season. In other climates, maximum biomasses are reported differently, in September-August in hyper-arid regions and temperate climates, or in March in tropical and subtropical climates (Šajna et al. 2007; Eid 2017; Galal et al. 2019).

The leaf area values are slightly higher than 27.22 cm^2, obtained in the same species by Carvalho et al. (2011) in a high altitude tropical climate, and of the same order of importance reported by Tedesco et al. (2019) in *Nymphoides humboldtiana* (Kunth) Kuntze, an aquatic plant native to the Americas (28.7-30.54 cm^2). Carvalho et al. (2011) also found a linear correlation of leaf area with the long-width product of plant leaf, whereas for this study, the later was highly correlated with leaf area of middle leaves by a power function.

4.2. Plant biomass

The average biomass of *Pistia* is within the class of the lowest productive Moroccan wetland plants, namely aquatic (*Lemna minor* and *L. gibba*), submerged (*Ruppia maritima* L.), floating submerged (*Ranunculus aquatilis* L.) or semi-aquatic species (*Cotula coronopifolia* L. and *Eleocharis palustris* (L.) Roem. & Schult.). It ranges from 23.93 to 164.87 g dw·m^{-2} estimated in natural and/or polluted environments respectively for the above ground biomass of *R. aquatilis* and the total biomass of *L. gibba* (Ennabili et al. 1998; Ennabili & Ater 2005). The same applies to similar aquatic species growing in temperate climates with sub-continental influence, such as *Lemna minor*, *Spirodela polyrhiza* (L.) Schleid. and *Ceratophyllum demersum*, with biomasses ranging from 64 to 119 g dw·m^{-2} (Steffenhagen et al. 2012).

In a microhabitat conserved upstream of Al Jawahir Wadi (Khabbach et al. 2019), *Pistia* plants reach a maximum of 55 cm, which can produce a maximum biomass of 157.16 g dw.m^{-2} according to Equation 4. This is 1.22 times the maximum biomass estimated in the study area, compared to 0.36 to 0.39 times those obtained in tropical, subtropical, and desert climates (Eid 2017; Galal et al. 2019), and 0.14 times that estimated in temperate climate (Šajna et al. 2007). The maximum root biomass assessed in this study, however, equates to 1.72 times that estimated under desert climate, compared to 0.68-0.75 times those reported under tropical and subtropical climates (Eid 2017; Galal et al. 2019). Root biomass is more representative in relation to total biomass (18.94%), significantly high compared to its equivalent in tropical and subtropical (15.27-15.58%) and desert climates (7.6%) (Eid 2017; Galal et al. 2019). Biomass production by *Pistia* could be favored by sunshine, high temperatures, and/or water loading with organic pollutants as partially suggested by Eid (2017). Control measures initiated early during its invasion, and habitat disturbance (SPV 2019; Khabbach et al. 2019) could also limit biomass production by this plant.

Depending on a mechanized control scenario, *Pistia* harvesting will provide a valuable biomass source for composting, vermiculture, livestock feed, or biogas production, with inoculation or mixed with cattle manure (Abbasi et al. 1991; Zennaki et al. 1996; Mishima 2008; Hussner et al. 2017; Gusain et al. 2018). This recovery option may also involve biomass from local aquatic, semi-aquatic, or riparian plants that share the same habitat as *Pistia* (Khabbach et al. 2019) and have been successfully tested in phytoremediation (Ennabili et al. 2019; Ennabili & Radoux 2020, 2021), in order to partially compensate harvesting costs, reduce disposal of phytomass in landfills, and avoid involuntary propagation of the viable parts of the collected plant.

4.3. N and P accumulation

The nitrogen concentration of the leafy part of *Pistia* is slightly lower than that of the root one, and vice versa for phosphorus, not concordant with the inference of Galal & Farahat (2015), having reported that the concentrations of macro-elements in the leaves are higher than those of the roots. Nitrogen and phosphorus contents of *Pistia* are in the range of those reported in different groups of local aquatic, helophytic and riparian plants. This plant locally accumulates nitrogen and phosphorus in values between those estimated in *L. minor* and *L. gibba*, i.e. 10.3 kg N - 0.69 kg P·ha^{-1} and 45.7 N - 2.5 P·ha^{-1}, respectively (Ennabili et al. 1998, 2000; Ennabili & Radoux 2006), but significantly below those reported by Steffenhagen et al. (2012) in *L. minor* and *S. polyrhiza* in a temperate climate. It should be noted that young plants of aquatic macrophytes may have higher nutrients concentrations compared to older ones, as was shown for total nitrogen and crude protein contents in relation to leaf area in *Pontederia crassipes* Mart. (Martins et al. 2011).

Considering the multitude of development cycles of *Pistia* during the same vegetation period, the periodic harvesting of the biomass when used in phytoremediation allows an annual export of about 23 times more nitrogen and 35 times more phosphorus (Lu et al. 2010) when compared to mineralomasses obtained *in situ*. However, the use of *Lemna gibba* L. in urban wastewater treatment in Mediterranean climate, with regular biomass harvesting, exceeded the retention of nitrogen and phosphorus by *Pistia* by factors of 8 and 16 times, respectively for similar applications (Ennabili et al. 2019). For such a purpose, and considering its current expansive invasion hazards, *Pistia* could not then constitute an alternative to *L. gibba*, a natural from Morocco and a successor of *Pistia* in Al Jawahir Wadi when water quality is highly degraded (Khabbach et al. 2019, 2020).

5. Conclusion

Comparison of functional aspects of *Pistia*, invading Al Jawahir Wadi, to other previous work under different climates suggests a likely progressive constitution of niches similar to continental, subtropical, tropical and desert climates. Estimation of leaf area index, biomass, and nitrogen and phosphorus mineralomasses in *Pistia* under these invasive conditions provided initial information for managers, when compared to other areas of the world. The mechanical control intervention could be carried out before the flowering stage while having significant collected biomasses and limiting the production of seeds. Moreover, exporting *Pistia* biomass before flowering would not have a significant effect on its nitrogen and phosphorus accumulation.

The *Pistia* biomass ranks among the lowest productive plants in Moroccan wetlands. Its harvesting, according to a mechanized control scenario, may allow the valorization of local plants sharing the same habitat and successfully tested in phytoremediation. In terms of biomass production, and nitrogen and phosphorus accumulation, compared to its native climate, *Pistia* would not yet reached its ideal developmental performance and offers opportunities for effective eradication actions.

Acknowledgments

The authors are grateful to their respective families for having accepted to cover part of this study costs.

References

Abbasi, S.A., Nipaney, P.C. & Panholzer, M.B. 1991. Biogas production from the aquatic weed *Pistia* (*Pistia stratiotes*). Bioresour. Technol. 37: 211–214.

Bello, A.O., Tawabini, B.S., Khalil, A.B., Boland, C.R. & Saleh, T.A. 2018. Phytoremediation of cadmium-, lead- and nickel-contaminated water by Phragmites australis in hydroponic systems. Ecol. Eng. 120: 126–133. https://doi.org/10.1016/j.ecoleng.2018.05.035

Carvalho, L.B., Souza, M.C., Bianco, M.S. & Bianco, S. 2011. Estimativa da área foliar de plantas daninhas de ambiente aquático: *Pistia stratiotes*. Planta Daninha 29(1): 65–68.

Cristaldi, A., Oliveri Conti, G., Luciano Cosentino, S., Mauromicale, G., Copat, C., Grasso, A., Zuccarello, P., Fiore, M., Restuccia, C. & Ferrante, M. 2020. Phytoremediation potential of Arundo donax (Giant Reed) in contaminated soil by heavy metals. Environ. Res. 185: 109427. https://doi.org/10.1016/j.envres.2020.109427

Driouech, F. 2010. Distribution des précipitations hivernales sur le Maroc dans le cadre d'un changement climatique: descente d'échelle et incertitudes. Dissertation. Université de Toulouse.

EPPO, European and Mediterranean Plant Protection Organization. 2017. Data sheets on pests recommended for regulation: *Pistia stratiotes* L. E.P.P.O. Bull. 47(3): 537–543. https://doi.org/10.1111/epp.12429

Eid, E.M. 2017. Verification of a numerical growth model of *Pistia stratiotes* L. using field data from tropical and subtropical sites. J. Freshw. Ecol. 32(1): 391–403. https://doi.org/10.1080/02705060.2017.1319430

Ennabili, A. & Ater, M. 2005. Diversité floristique et production de biomasse des macrophytes des marais Smir. Trav. Inst. Sci. Rabat Sér. Gén. 4: 17–25. https://doi.org/10.6084/m9.figshare.12943091.v1

Ennabili, A. & Radoux, M. 2006. Teneurs en azote, phosphore et potassium (NPK) d'hygrophytes du Maroc méditerranéen. Acta Bot. Barc. 50: 459–464.

Ennabili, A. & Radoux, M. 2020. Nitrogen and phosphorus removal efficiency of three helophytes in constructed surface flow wetlands for urban wastewater treatment. IIUM Eng. J. 21(2): 25–40. https://doi.org/10.31436/iiumej.v21i2.1207

Ennabili, A. & Radoux, M. 2021. Nitrogen and phosphorus uptake and biomass production in four riparian plants grown in subsurface flow constructed wetlands for urban wastewater treatment. J. Environ. Manage. 280: 111806. https://doi.org/10.1016/j.jenvman.2020.111806

Ennabili, A., Ater, M. & Radoux, M. 1998. Biomass production and NPK-retention in macrophytes from wetlands of the Tingitan Peninsula. Aquat. Bot. 62(1): 45–56. https://doi.org/10.1016/S0304-3770(98)00075-8

Ennabili, A., Ater, M. & Radoux, M. 2000. Biomasse et Accumulation des NPK chez Scirpus litoralis Schrader et Scirpus maritimus L. aux marais Smir-Negro (NW du Maroc). Acta Bot.Barc. 46: 239–250.

Ennabili, A., Ezzahri, J. & Radoux, M. 2019. Performance of Lemna gibba bioreactor for nitrogen and phosphorus retention, and biomass production in Mediterranean climate. J. Environ. Manage. 252: 109627. https://doi.org/10.1016/j.jenvman.2019.109627

Ennabili, A., Libiad, M. & Khabbach, A. 2021. Importance of Wetlands in Maintaining the Richness of Morocco's Vascular Flora. Wetl. 41(121): 1–10. https://doi.org/10.1007/s13157-021-01517-3

Galal, T.M. & Farahat, E.A. 2015. The invasive macrophyte *Pistia stratiotes* L. as a bioindicator for water pollution in Lake Mariut, Egypt. Environ. Monit. Assess. 187: 701. https://doi.org/10.1007/s10661-015-4941-4

Galal, T.M., Dakhil, M.A., Hassan, L.M. & Eid, E.M. 2019. Population dynamics of *Pistia stratiotes* L. Rend. Lincei-Sci. Fis. 30: 367–378. https://doi.org/10.1007/s12210-019-00800-0

Gusain, R., Pandey, B. & Suthar, S. 2018. Composting as a sustainable option for managing biomass of aquatic weed *Pistia*: A biological hazard to aquatic system. J. Clean Prod. 177: 803–812. https://doi.org/10.1016/j.jclepro.2017.12.261

Hussner, A., Stiers, I., Verhofstad, M.J.J.M., Bakker, E.S., Grutters, B.M.C., Haury, J.,van Valkenburg, J.L.C.H., Brundu, G., Newman, J., Clayton, J.S., Anderson, L.W.J. & Hofstra, D. 2017. Management and control methods of invasive alien freshwater aquatic plants: A review. Aquat. Bot. 136: 112–137. http://dx.doi.org/10.1016/j.aquabot.2016.08.002

KangaIdé, S., Naimi, M. & Chikhaoui, M. 2021. Assessment of surface water quality using indices and geographic information system in the Sebou river basin, Morocco. Eur. Sci. J. 17(10): 249–269. https://doi.org/10.19044/esj.2021.v17n10p249

Khabbach, A., Libiad, M. & Ennabili, A. 2019. Invasion increasing risk of Al Jawahir Wadi lentic habitats by *Pistia stratiotes* L. (North-Central Morocco).

Bot. Complut. 43: 97–107. https://doi.org/10.5209/bocm.64280

Khabbach, A., Libiad, M. & Ennabili, A. 2020. An updated checklist of the wetland vascular flora from Morocco. Moroc. J. Biol. 17: 1–35. https://doi.org/10.6084/m9.figshare.12937823.v3

Lu, Q., He, Z.L., Graetz, D.A., Stoffella, P.J. & Yang, X. 2010. Phytoremediation to remove nutrients and improve eutrophic stormwaters using water lettuce (*Pistia stratiotes* L.). Environ. Sci. Pollut. Res. Int. 17(1): 84–96. https://doi.org/10.1007/s11356-008-0094-0

Lu, Q., He, Z.L., Graetz, D.A., Stoffella, P.J. & Yang, X. 2011. Uptake and distribution of metals by water lettuce (*Pistia stratiotes* L.). Environ. Sci. Pollut. Res. 18: 978–986. https://doi.org/10.1007/s11356-011-0453-0

Martins, D.F.F., Moura, M.F.V., Souza, L.D., Camacho, R.G.V., Silva, A.G. & Rocha, L.N.G. 2011. Determinação de nitrogênio total e proteína bruta em Eichhornia crassipes presentes no rio Apodi / Mossoró - RN. Perióđ. Tchê. Quím. 8(15): 7–13.

Matrat, R., Haury, J., Anras, L., Lambert., E, Lacroix., P, Guédon., G. et al. 2012. Gestion des plantes exotiques envahissantes en cours d'eau et zones humides – Guide technique. Pays de la Loire, France.

Mishima, D. 2008. Ethanol production from candidate energy crops : Water hyacinth (Eichhornia crassipes) and water lettuce (*Pistia stratiotes* L.). Bioresour. Technol. 99(7): 2495–2500. https://doi.org/10.1016/j.biortech.2007.04.056

Nouga Bissoue, A., Enjoh, N., Ndjouondo, G.P. & Dibong, S.D. 2017. Aspects socio-économiques de la lutte contre les plantes aquatiques envahissantes du fleuve Nyong dans la Commune de Mbalmayo. Int. J. Innov. Appl. Stud. 19(2): 363–375.

Prajapati, S.K., Meravi, N. & Singh, S. 2012. Phytoremediation of Chromium and Cobalt using *Pistia stratiotes*: A sustainable approach. Proc. Int. Acad. Ecol. Environ. Sci. 2(2): 136–138.

SPV, Service de la Protection des Végétaux, Fès. *Pistia stratiotes* L. https://studylibfr.com/doc/351066/*pistia-stratiotes*-l [Access April 2019].

Šajna, N., Haler, M., Škornik, S. & Kaligaric, M. 2007. Survival and expansion of *Pistia stratiotes* L. in a thermal stream in Slovenia. Aquat. Bot. 87: 75–79. https://doi.org/10.1016/j.aquabot.2007.01.012

Santos, M.J., Anderson, L.W. & Ustin, S.L. 2011. Effects of invasive species on plant communities: An example using submersed aquatic plants at the regional scale. Biol. Invasions 13: 443–457. https://doi.10.1007/s10530-010-9840-6

Sasmaz, M., Arslan Topal, E.I., Obek, E. & Sasmaz, A. 2015. The potential of *Lemna gibba* L. and *Lemna minor* L. to remove Cu, Pb, Zn, and As in gallery water in a mining area in Keban, Turkey. J. Environ. Manage. 163: 246–253. http://dx.doi.org/10.1016/j.jenvman.2015.08.029

Steffenhagen, P., Zak, D., Schulz, K., Timmermann, T. & Zerbe, S. 2012. Biomass and nutrient stock of submersed and floating macrophytes in shallow lakes formed by rewetting of degraded fens. Hydrobiol. 692: 99–109. https://doi.org/10.1007/s10750-011-0833-y

Stiers, I., Crohain, N., Josens, G. & Triest, L.2011. Impact of three aquatic invasive species on native plants and macroinvertebrates in temperate ponds. Biol. Invasions 13: 2715–2726. https://doi.org/10.1007/s10530-011-9942-9

Tedesco, C.D., Petry, C., Bortoluzzi, E.C. & Castamann, A. 2019. Using White Star (Nymphoides humboldtiana) for lake landscaping. Hortic. Bras. 37: 133–137. http://dx.doi.org/10.1590/S0102-053620190202

Villamagna, A.M. & Murphy, B.R. 2010. Ecological and Socio-Economic Impacts of Invasive Water Hyacinth (*Eichhornia crassipes*). Freshw. Biol. 55(2): 282–98. https://doi.org/10.1111/j.1365-2427.2009.02294.x

Zennaki, Z., Boulif, M., Zaid, A. & Bentaya, K. 1996. Optimization of Anaerobic digestion of cattle manure Effect of its association with the aquatic weed *Pistia* (*Pistia stratiotes*). Al Awamia 93: 27–39.

Živković, M.M., Anđelković, A.A., Cvijanović, D.L., Novković, M.Z., Vukov, D.M., Šipoš, Š.Š., Ilić, M.M., Pankov, N.P., Miljanović, B.M., Marisavljević, D.P., Pavlović, D.M. & Radulović, S.B. 2019. The beginnings of *Pistia stratiotes* L. invasion in the lower Danube delta: the first record for the Province of Vojvodina (Serbia). BioInvasions Rec. 8(2): 218–229. https://doi.org/10.3391/bir.2019.8.2.03

Tables

Table 1. River water instantaneous characteristics.

Parameters	Non-filtered sample	Filtered sample
pH	6.81±0.02	.
T (°C)	22.32±0.42	.
DO (mg·l-1)	3.74±0.26	.
Ec (μS·cm-1)	1250±40.73	.
TDS (mg·l-1)	6.25±0.21	.
PSU (g·kg-1)	0.63±0.02	.
TSS (mg·l-1)	77.75±7.81	.
COD (mg.l-1)	110.3±8.06	14.02±5.44
TN (mg·l-1)	8.09±0.9	2.01±1.67
N-NO3 (mg·l-1)	1.26±0.36	0.88±0.43
TP (mg·l-1)	1.65±0.66	*
TC (MPN/100ml)	1.2	.
FC (MPN/100ml)	0.8	.

* Not measurable by the method used. COD, Chemical Oxygen Demand. DO, Dissolved Oxygen. Ec, Electrical Conductivity. FC, Faecal Coliforms. MPN, Most Probable Number. $N\text{-}NO_3$, Nitrates. pH, Hydrogen Potential. PSU, Practical Salinity Unit. T, Temperature. TC, Total Coliforms. TDS, Total Dissolved Solids. TN, Total Nitrogen. TP, Total Phosphorus. TSS, Total Suspended Solids.

Table 2. Correlation between leaf area (LA) and leaf size in *Pistia* (N=90).

	Parameter	Mean±SD	Trend curve equation	R2
Outer leaf	L (cm)	9.31±2.43	$LA = 1.314 \cdot L^{1.359}$	0.571
	W (cm)	4.65±1.04	$LA = 1.789 \cdot W^{1.773}$	0.723
	L·W (cm2)	45.13±19.62	$LA = 1.134 \cdot (L \cdot W)^{0.846}$	0.700
Middle leaf	L (cm)	9.51±2.50	$LA = 0.924 \cdot L^{1.562}$	0.700
	W (cm)	5.15±1.37	$LA = 2.217 \cdot W^{1.608}$	0.667
	L·W (cm2)	51.09±23.16	$LA = 0.994\ (L \cdot W)^{0.886}$	0.771

L and W, Leaf length and maximum width.

Figures

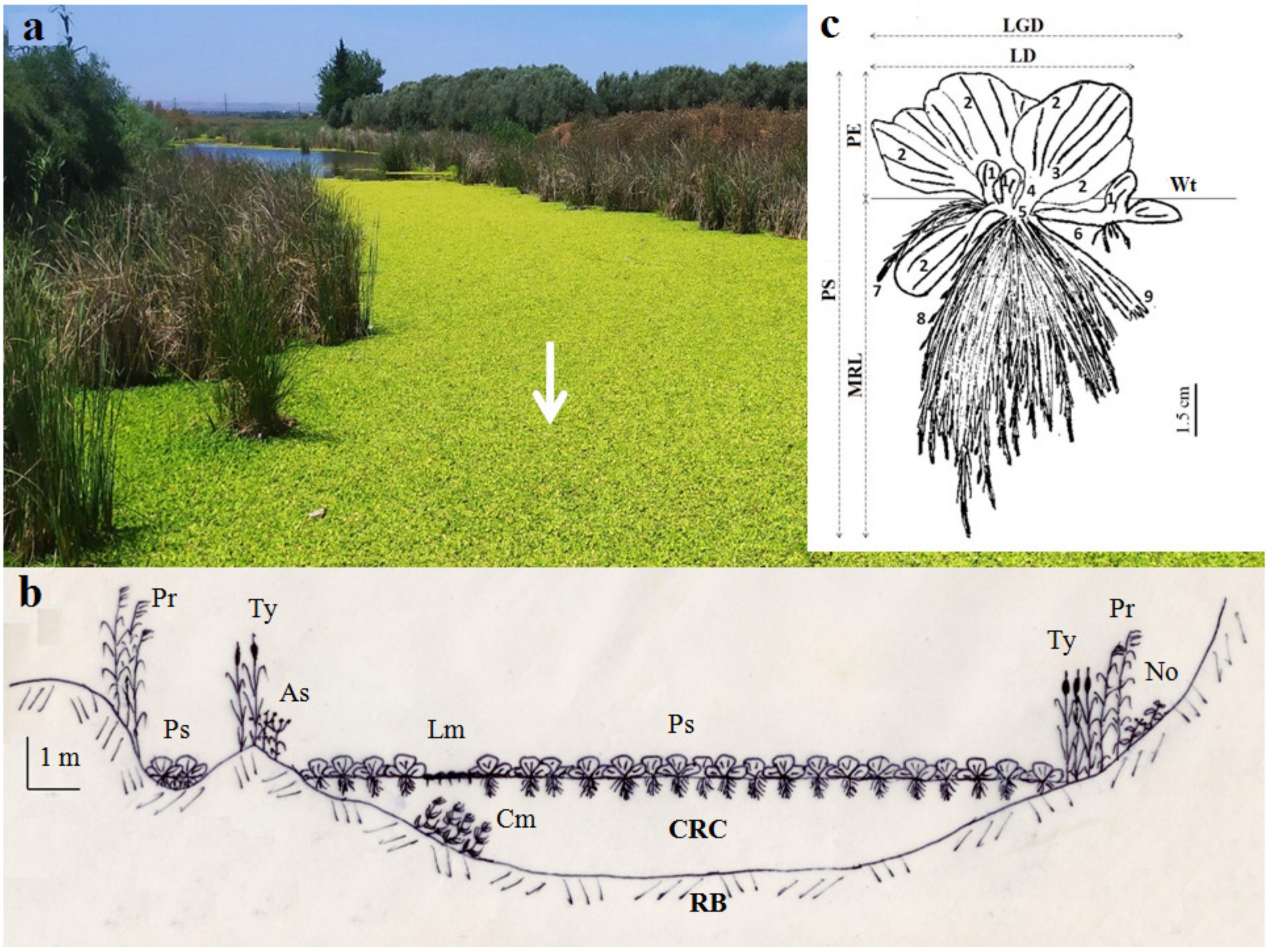
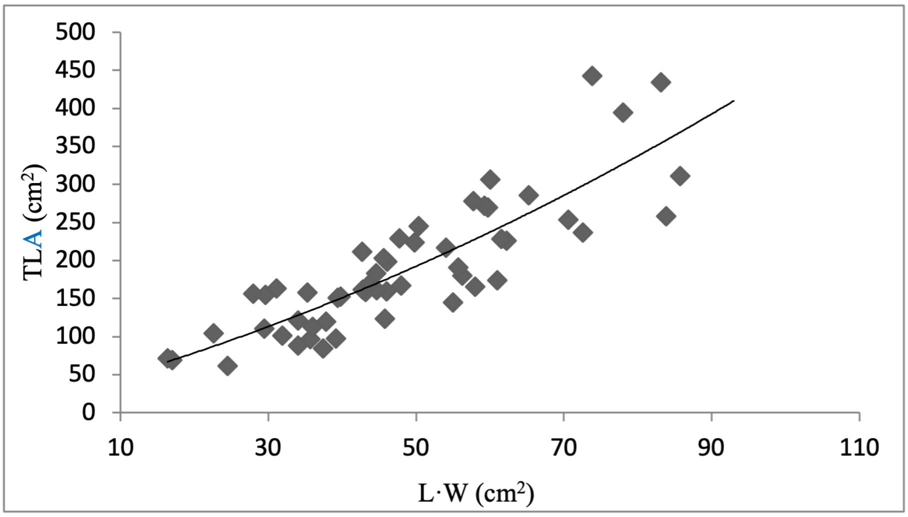
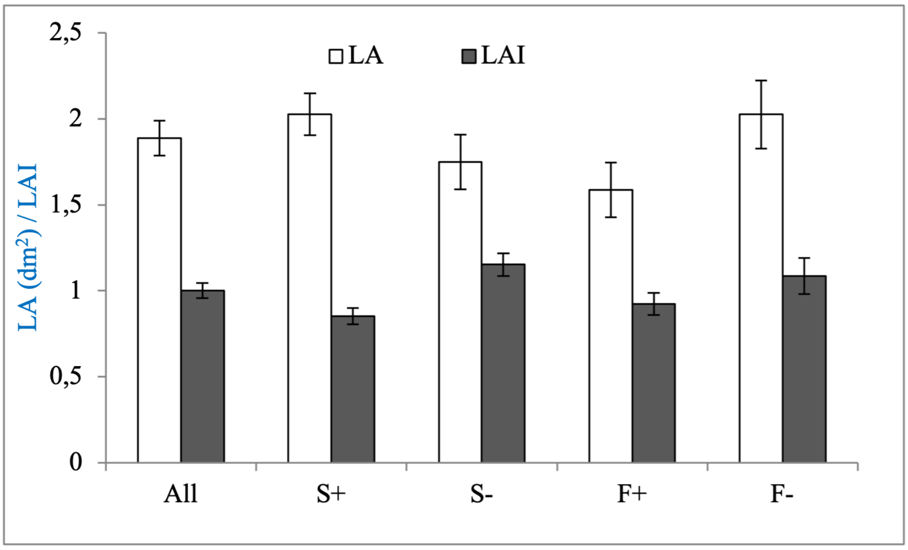


Figure 1. Sampling location. (a) View during the growing season; the arrow indicates the river's cross-sectional level (b). As, *Symphyotrichum squamatum* (Spreng.) G.L. Nesom; Cm, *Ceratophyllum demersum* L.; CRC, central river course; Lm, *Lemna minor* L.; No, *Nasturtium officinale* R. Br.; Pr, *Phragmites australis* (Cav.) Trin. ex Steud.; Ps, *Pistia stratiotes* L.; RB, river bottom; Ty, *Typha angustifolia* L. (c) Plant diagram of *P. stratiotes* plant showing descriptive details (Khabbach et al. 2019). LD, leaf rosette-diameter; LGD, leaf rosette-global diameter; MRL, maximum root length; PE, plant height; PS, plant size; Wt, water level. 1, offspring; 2, outer leaf; 3, ribs; 4, petiole; 5, collar; 6, stolon; 7-8, cap of primary (7) and secondary (8) roots; 9, senescing leaf.

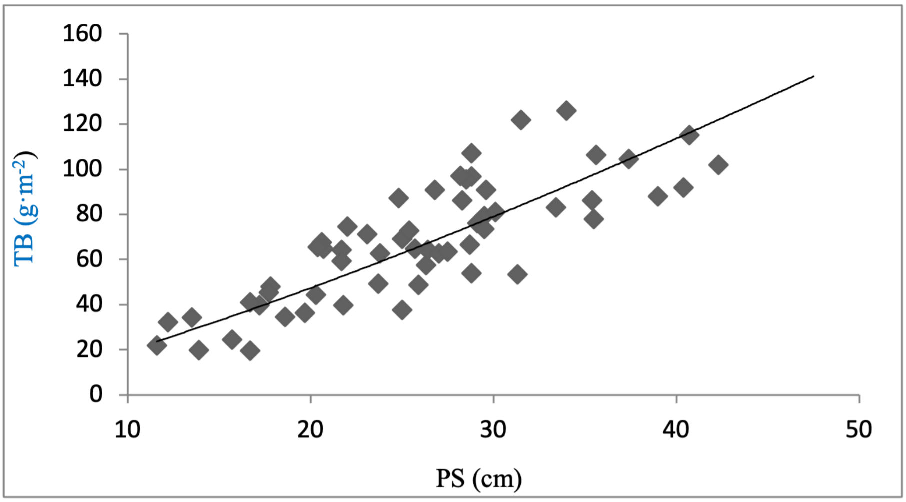


-a-

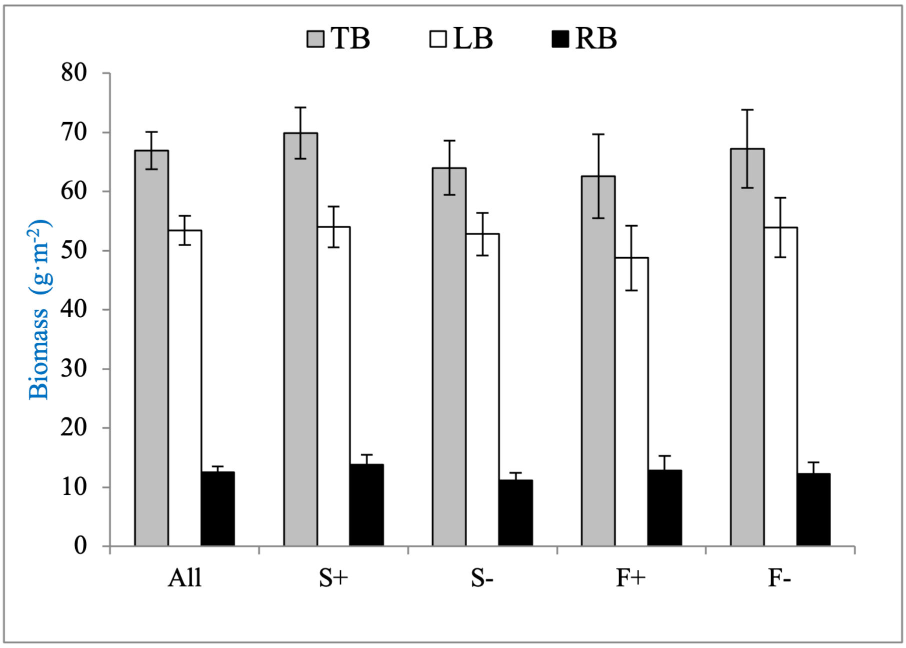


-b-

Figure 2. Plant leaf area of *Pistia*: **a**. Relationship between the total plant leaf-area (TLA) and the "length·maximum width" (L·W) of the outer leaf. **b**. Leaf-area (LA) and leaf-area index (LAI) according to the presence (+) and absence (-) of stolons (S) and/or inflorescences (F).



-a-



-b-

Figure 3. Biomass assessment in *Pistia*: **a**. Total biomass (TB) depending on the plant size (PS). **b**. Biomass according to the presence (+) and absence (-) of stolons (S) and/or inflorescences (F). LB, Biomass above water surface; RB, Root biomass; TB, Total biomass.