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Original article

Nutrient sequestration potential of water primrose *Ludwigia stolinefera* (Guill. & Perr.) P.H. Raven: A strategy for restoring wetland eutrophication

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ABSTRACT

The current work investigates the capacity of the water primrose (*Ludwigia stolinefera*) to sequester inorganic and organic nutrients in its biomass to restore eutrophic wetlands, besides its nutritive quality as fodder for animals. The nutrient elements and nutritive value of the water primrose were assessed seasonally in polluted and unpolluted watercourses. The water primrose plants' highest biomass was attained during summer; then, it was significantly reduced till it reached its lowest value during winter. In the polluted canal, the plant root and shoot accumulated higher contents of all nutrient elements (except Na and Mg) rather than in the unpolluted Nile. They accumulated most investigated nutrients in the growing season during summer. The shoots accumulated higher contents of N, P, Ca, and Mg than the root, which accumulated higher concentrations of Na and K. Therefore, summer season is the ideal time to harvest water primrose for removing the maximum nutrients for restoring eutrophic watercourses. The aboveground tissues had the highest values of ether extract (EE) during spring and the highest crude fibers (CF) and total proteins (TP) during summer. In contrast, the belowground tissues had the lowest EE, CF, and TP during winter. In spring, autumn, and winter seasons, the protein content in the grazeable parts (shoots) of the water primrose was within the range, while in summer, it was higher than the minimum requirement for the maintenance of animals. There was a decrease in crude fibers and total proteins, while an increase in soluble carbohydrates content in the below- and above-ground tissues of water primrose under pollution stress. The total protein, lipids, and crude fibers of the aboveground parts of water primrose support this plant as a rough forage.

1. Introduction

Aquatic macrophytes, including floating life forms, regulate freshwater ecosystem services respecting nutrient remediation and water purification (Manolaki et al. 2020). Aquatic plants can sequester high amounts of nutrients from wetlands by storing them in the roots and/or shoots (Lai et al., 2011; Eid et al., 2020). Consequently, these plants are significant nutrient cycling components because they may collect nutrients from their environment into new organs during the growing period (Kröger et al. 2007). Aquatic plants need nutrients for their growth and reproduction, whereas these plants are very productive; thus, extensive contents of nutrients can be incorporated into their biomass (Vymazal 2020). The high production of these plants can take up large quantities of nutrients from their surroundings. Thus they have been used to diminish significant nutrients from domestic, industrial, and agricultural wastewater (Vymazal 2008).

Luxury uptake of nutrients by plants is a mechanism by which plants assimilate excessive nutrients for everyday metabolic purposes (Cronk and Fennessy 2001). Nutrient pollutants such as nitrogen and phosphorus are significant sources for environmental pollution because they support undesired algal blooms (Krimsky et al. 2021). The characterization of these nutrients in aquatic

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ecosystems are essential as they directly influence water quality and the global carbon budget (Taillardat et al. 2020). Several sources of nutrients, including sewage, agricultural drainage, pet wastes, and fertilizers, have been khnown to rise nutrient loads in surface water (Jani et al., 2020; Lusk et al., 2020). Increasing water demands, population growth, and environmental degradation have attracted attention towards wetland restoration (Krimsky et al. 2021).

Nutrients concentrations in aquatic ecosystems have increased due to socio-economic development and intensive anthropogenic activities resulting in eutrophication and, consequently, ecosystem degradation (Wu et al. 2021). For decades, an excessive nutrient in aquatic ecosystems is considered a worldwide challenge due to its consequence of eutrophication (Huang et al. 2020). For example, excessive fertilizers, which often go beyond the actual requirement of crops, can lead to the discharge of nutrients, especially phosphorus and nitrogen, from cultivated lands into watercourses (Kiani et al. 2021). Excessive nutrients accumulate in wetland bottoms, however they may be recycled back to the overlying water and, consequently, sustain eutrophication risks (Kiani et al., 2020). Aquatic plants can contribute to ecosystem restoration by eliminating pollutants from water and sediment and transfer them to their aboveground biomass (kumwimba et al. 2020). Therefore, regular harvesting of aquatic plants enhances the treatment effectiveness and prevents decayed plants from reentering the water body (Vymazal and Březinová, 2018). To restore and manage aquatic ecosystems, the removal of aboveground biomass is a common practice to establish low nutrient conditions (Geurts et al. 2020). Harvesting plants can reach optimum nutrient removal efficiency at their maximum biomass production and nutrient contents (Meuleman et al. 2002).

In recent years, population growth and land desertification have increased the demand for forage products (Tanaka et al. 2017). Simultaneously, the system of forage production faces difficulties due to the interference with food crop production and the decrease in the expansion of agricultural land (Bruinsma, 2003). Consequently, in developing countries, there is an urgent need for the exploitation of alternative feed resources. Feeding non-traditional feedstuffs may reduce feed costs for animal producers, whereas this alternative feedstuff may contain high fibers, affecting digestibility and hence meat quality (Rattanasomboon et al. 2019). The present study's main objectives are to investigate the seasonal potential of the floating plant *Ludwigia stolonifera* for sequestering nutrients from polluted water and its possible use as fodders for animals.

2. Material and methods

2.1. Study species

Ludwigia stolonifera (Guill. & Perr.) P.H. Raven (Onagraceae family), known as water purslane or water primrose, is perennial water creeping plant with floating shoots and belowground roots (Galal et al. 2019a). It is widely distributed in Middle East countries including Syria, Turkey, Palestine, Lebanon, and Egypt (Kavak, 2014). Water primrose is an invasive aquatic plant, which causes risks to the aquatic ecosystems through its high growth and propagation rates under nutrient-rich conditions (Saleh et al. 2019). As reported by Galal et al. (2012), it is one of the commonest aquatic plants in the Nile Delta watercourses as well as in the Egyptian Northern Lakes. Water primrose forms dense mats, which retard the water flow and block the whole watercourse as well as threaten biodiversity (Soliman et al., 2018; Galal et al., 2019a). Water primrose can grow out from the water bank for a great distance to support floats (Abu-Ziada 2007). It can be used for water and sediment phytoremediation and improve water quality (Khalifa et al. 2017).

2.2. Plant sampling and biomass estimation

A sampling of the water primrose plants was carried out seasonally through six sites at the Ismailia canal, which branches from the River Nile, and receives effluents of several domestic, municipal, and industrial activities from the adjacent area (Fig. 1). As a reference, two unpolluted sites were selected, during summer and winter, on the River Nile, the primary source of drinking water for Egyptians. Three quadrats (0.5 × 0.5 m) were selected randomly to represent the growth of water primrose plants at each site. All plant shoots, in each quadrat, were cut off at the sediment surface and transferred to the laboratory in polyethylene bags. The sampled shoots were washed with de-ionized water, left to air dry, and then oven-dried at 65 °C to constant weight for estimating their aboveground biomass (g DW m^{-2}).

2.3. Plant analysis

2.3.1. Inorganic nutrients

Three composite samples from the aboveground (stem and leaves), and belowground (rhizome and roots) parts of water primrose were collected seasonally from each site. Samples were oven-dried, homogenized by grinding in a metal-free plastic mill, and then passed through a sieve of 2 mm mesh size. About 1 g of the ground samples was digested mixed-acid digestion method. Total nitrogen (N) was determined by the Kjeldahl method, while P was estimated by molybdenum blue method using spectrophotometer (CECIL CE 1021), Ca, Na, and K were analyzed using a flame photometer (CORNING M410), and Mg was measured using Shimadzu AA-6200 atomic absorption photometer. The procedures mentioned above for plant analysis were gathered from Allen (1989).

2.3.2. Organic nutrients

Crude fats were determined by extracting the plant with ether and crude fibers were determined by the Soxhlet extraction method (Allen 1989). The total protein content was estimated by multiplying N-concentration by the factor 6.25 (Adesogon et al. 2000). Carbohydrate (NFE) was evaluated according to the equation (Le Houérou 1980):

$$\mathrm{NFE}\quad(\mathrm{in\%drymatter}) = 100 - (\mathrm{TP} + \mathrm{CF} + \mathrm{crudefat} + \mathrm{ash}) \qquad (1)$$

Given that TP: total protein and CF = crude fiber. Digestible crude protein (DCP) was estimated according to the equation (Demarquilly and Weiss, 1970):

$$\mathrm{DCP(in\%drymatter)} = 0.929\mathrm{TP(in\%drymatter)} - 3.52. \qquad (2)$$

Total digestible nutrients (TDN) was estimated according to the equation applied by Naga and El-Shazly (1971):

$$\mathrm{TDN(in\%drymatter)} = 0.623(100 + 1.25\mathrm{EE}) - \mathrm{CP}0.72 \qquad (3)$$

where EE and CP are the ether extract and crude protein percentages, respectively. Digestible energy (DE) was evaluated following this equation (NRC, 1984):

$$\begin{aligned}\mathrm{DE(Mcalkg} - 1) = {} & 0.0504\mathrm{TP}(\%) + 0.077\mathrm{EE}(\%) + 0.02\mathrm{CF}(\%) \\ & + 0.000377(\mathrm{NFE})^2(\%) + 0.011(\mathrm{NFE})(\%) \\ & - 0.152. \end{aligned} \qquad (4)$$

$$\mathrm{Metabolizedenergy(ME)wascalculatedas(Garrett1980)}: \mathrm{ME} = 0.82\mathrm{DE} \qquad (5)$$

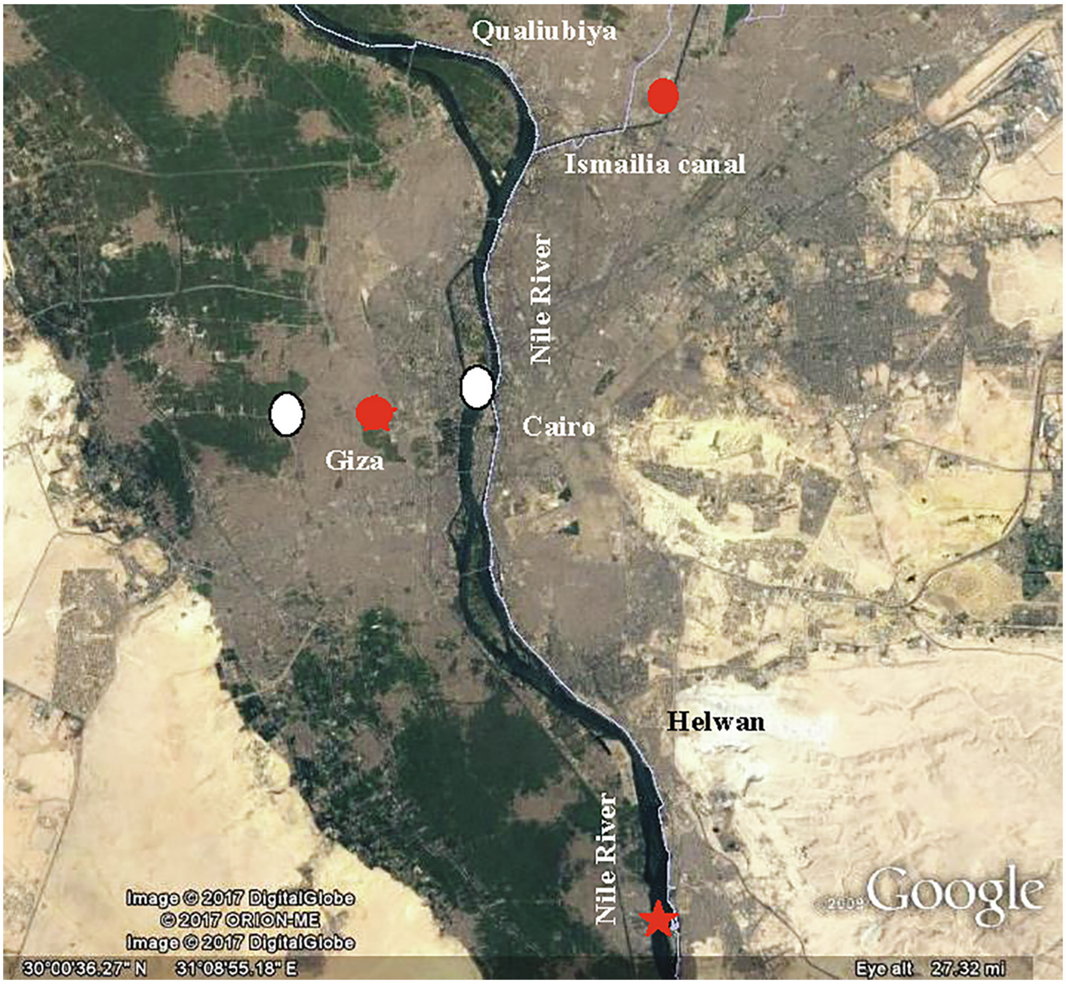

Fig. 1. Location map showing the unpolluted (fx1) and the polluted (fx2) sites of the study area. 30° 00′ 36.27″ N and 31° 08′ 5.18″ E. Source: Google earth on 19 April 2017.

$$\text{Netenergy(NE)} = 0.50\text{ME(LeHouérou1980)} \quad (6)$$

Moreover, gross energy (GE) was calculated following the equation (NRC 1984):

$$\text{GE(Kcal100g} - 1) = 5.72\text{TP}(\%) + 9.5\text{EE}(\%) + 4.79\text{CF}(\%) + 4.03\text{NFE}(\%) \quad (7)$$

2.4. Water and sediments analyses

For chemical analysis, three composite samples (1-liter each) from the surface water of the study watercourses were collected from each site. Nutrient elements were determined using the standard methods of Allen (1989). The Kjeldahl method was used to assess the total nitrogen (N), while molybdenum blue method using a spectrophotometer (CECIL CE 1021) was used to determine P, and the flame photometer (CORNING M410) was used to analyze Na and K were determined using. Chlorides were estimated by direct titration against silver nitrate solution using 5% potassium chromate as an indicator. The bicarbonate content was estimated by titration against 0.01 N HCl, while sulphates were estimated turbidimetrically as barium sulphate at 500 nm. On the other hand, three composite sediment samples were collected from each site using stainless steel crab. Sediment samples were dried, ground, and sieved through 2 mm sieve. Sediment-water extract of 1:5 was prepared to determine pH and EC using pH meter Model 9107 BN (ORION type) and conductivity meter 60 Sensor Operating Instruction Corning, respectively. In addition, sediment N, P, K, Na, Cl, HCO_3, and SO_4 were estimated with the same water analysis procedure (Allen, 1989).

2.5. Data analysis

A Paired-sample *t*-test was applied to assess the differences in the sediment and water variables between the polluted and unpolluted watercourses. In addition, one-way analysis of variance (ANOVA) was used to evaluate the significance of seasonal variations of nutrients among the different plant organs, after testing the data for normality and homogeneity of variance, according to SPSS software (SPSS, 2012).

3. Results

3.1. Water and sediments characteristics

The chemical analysis of water and sediment exhibited significant differences in water pH, EC, N, P, and K, and sediment pH, EC, HCO_3, SO_4, N, Na, and K, between polluted and unpolluted watercourses (Table 1). Most of the investigated variables (except HCO_3 and Na) were accumulated in the sediment rather than the water.

Table 1
Variation in the mean ± standard deviation of the water and sediment characteristics of *Ludwigia stolonifera* in polluted and unpolluted watercourses.

Variable	Water		t-vale	Sediment		t-vale
	Unpolluted	Polluted		Unpolluted	Polluted	
PH	6.3 ± 0.4	7.6 ± 0.4	2.5*	7.0 ± 0.2	5.1 ± 0.4	2.6*
EC (μS cm^{-1})	265.6 ± 10.2	452.0 ± 9.6	3.4*	392.7 ± 2.9	486.4 ± 8.8	2.8*
Nutrients	**mg l^{-1}**			**mg kg^{-1}**		
HCO_3	400.0 ± 7.6	415.2 ± 13.3	0.8	248.9 ± 28.7	396.5 ± 32.1	2.5*
Cl	82.4 ± 8.7	100.0 ± 5.8	1.7	156.5 ± 22.1	231.2 ± 24.3	1.3
SO_4	50.1 ± 3.3	51.1 ± 3.4	1.2	251.3 ± 9.8	350.0 ± 82.1	3.3*
Total N	191.1 ± 25.4	413.2 ± 12.2	5.7**	1340.4 ± 121.2	2230.3 ± 321.2	3.1*
P	51.1 ± 4.6	92.1 ± 10.9	2.6*	81.8 ± 10.1	94.9 ± 21.1	0.9
Na	214.1 ± 12.6	233.3 ± 21.3	0.8	142.7 ± 6.2	213.5 ± 6.7	2.6*
K	15.7 ± 9.8	19.7 ± 2.4	2.7*	124.6 ± 6.9	143.8 ± 10.8	2.8*

*: $p < 0.05$, **: $p < 0.01$.

3.2. Biomass assessment

Remarkable seasonal variation in the biomass of the water primrose was documented (Fig. 2). The highest biomass (512.6 g DW m^{-2}) was recorded during summer, which exhibited a significant difference with the lowest value (297.2 g DW m^{-2}) recorded during winter. The biomass of water primrose from the unpolluted canal (405.7 g DW m^{-2}) was not significantly different from those recorded during spring and autumn (400.0 and 412.8 g DW m^{-2}) in the polluted Nile. For comparing the water primrose's annual biomass, no significant difference between polluted and unpolluted watercourses was recognized.

3.3. Inorganic nutrients content

The inorganic nutrient analysis of the water primrose's shoot and root revealed significant seasonal variation (Table 2). Summer season donated the highest contents of plant Na (233.2 mg kg^{-1}) in its roots and total N (2.2%) in its shoots, while the highest K (321.6 mg kg^{-1}) and P (1.4%) was recorded in the roots and shoots, respectively during spring. Moreover, the plant shoot had the highest Ca (1.8%) during autumn, whereas the highest Mg (0.4%) during spring, summer, and winter. On the other hand, the winter season contributed the lowest contents of Na and K (140.1 mg kg^{-1} and 181.2 mg kg^{-1}) in the plant shoot and total N (0.5%) in its roots. while the lowest Ca (0.4%) was recorded in the plant root during winter. Comparing the nutrient content of the different water primrose tissues from the polluted canal with those of unpolluted Nile showed no significant differences in the investigated elements (except Na) in the roots. At the same time, there were substantial differences in these elements (except K and Mg) in the plant shoot (Table 3). It is worth noting that the below- and above-ground plant parts accumulated higher contents of all nutrient elements (except Na and Mg) from polluted rather than unpolluted watercourses.

3.4. Organic nutrients content

Organic nutrients analysis in the above- and belowground parts of the water primrose exhibited significant seasonal variation in all investigated nutrients (Table 4). The aboveground tissues had the highest values of ether extract (EE) and the lowest ash content (1.8 and 6.3%), respectively during spring, while the highest crude fibers (CF) and total proteins (TP) (36.5 and 5.6%), but the lowest carbohydrates (NFE) (40.6%) during summer. On the other hand, the belowground tissues had the highest contents of ash and NFE

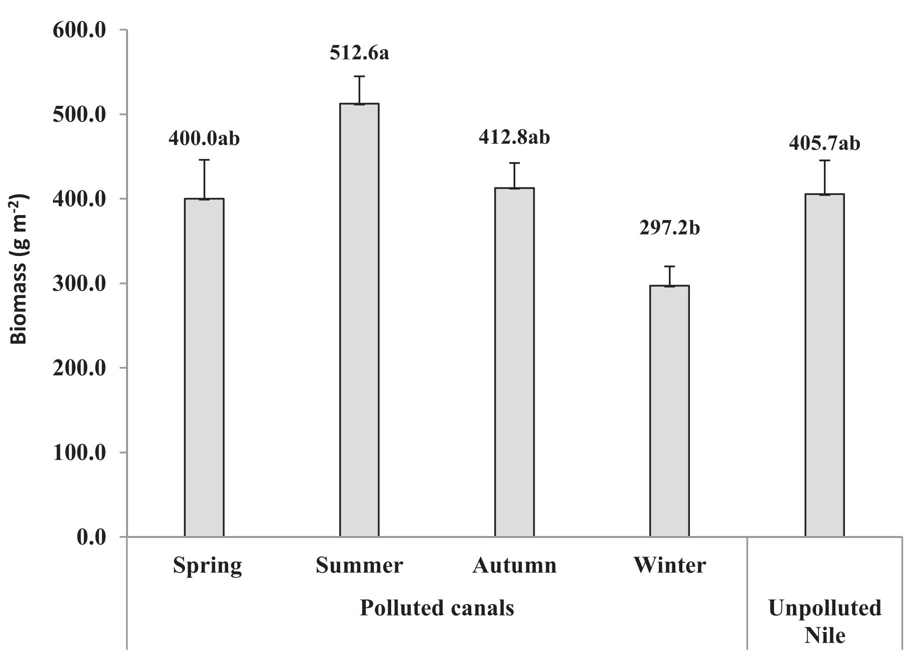

Fig. 2. Dry biomass of the above-ground parts of *Ludwigia stolonifera* collected from polluted and unpolluted watercourses.

Table 2
Seasonal variation in the mean ± standard deviation of the inorganic nutrients of the different organs of *Ludwigia stolonifera* collected from the polluted canal. R: belowground roots, S: aboveground shoots. Maximum and minimum values are underlined.

Season			Na (mg kg^{-1})	K (mg kg^{-1})	Total N (%)	Ca (%)	P (%)	Mg (%)
Polluted canals	**Spring**	**R**	209.3 ± 23.5ab	321.6 ± 31.4a	0.7 ± 0.1ef	0.4 ± 0.1d	0.6 ± 0.1de	0.2 ± 0.0c
		S	176.5 ± 10.3bc	247.9 ± 19.1bc	1.3 ± 0.3c	0.8 ± 0.2bc	1.4 ± 0.2a	0.4 ± 0.1a
	Summer	**R**	233.2 ± 32.1a	297.1 ± 59.9ab	0.9 ± 0.4d	0.7 ± 0.3 cd	0.4 ± 0.1 fg	0.2 ± 0.1bc
		S	162.9 ± 30.7bc	230.3 ± 13.6 cd	2.2 ± 0.3a	1.2 ± 0.4b	0.6 ± 0.1 cd	0.4 ± 0.1a
	Autumn	**R**	154.8 ± 33.8bc	197.4 ± 26.4 cd	0.7 ± 0.2ef	0.8 ± 0.1 cd	0.4 ± 0.1 fg	0.1 ± 0.0c
		S	145.1 ± 17.5c	194.7 ± 5.6 cd	1.8 ± 0.3ab	1.8 ± 0.3a	0.8 ± 0.1bc	0.2 ± 0.0bc
	Winter	**R**	167.6 ± 10.5bc	219.0 ± 17.9 cd	0.5 ± 0.1f	0.5 ± 0.1 cd	0.4 ± 0.1ef	0.1 ± 0.0c
		S	140.1 ± 27.7c	181.2 ± 39.3d	1.6 ± 0.4bc	0.7 ± 0.2 cd	0.9 ± 0.1b	0.4 ± 0.1a
F-value			**2.7****	**6.1*******	**16.9*******	**11.5*******	**38.3*******	**7.3*******

Means with the same letters are not significant according to Duncan's test. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

Table 3
Mean ± standard deviation of the inorganic nutrients of the different organs of *Ludwigia stolonifera* collected from polluted (P) and unpolluted (U) watercourses.

Inorganic element		Root		t-value	Shoot		t-value
		P	U		P	U	
Na	**mg kg^{-1}**	183.9 ± 36.4	153.1 ± 35.7	**2.8***	156.1 ± 16.7	135.3 ± 28.4	2.2*
K	**mg kg^{-1}**	246.5 ± 59.9	205.1 ± 47.8	**1.2**	213.6 ± 30.9	212.4 ± 26.7	**1.3**
Total N	**%**	0.7 ± 0.2	0.9 ± 0.2	**1.1**	1.7 ± 0.4	2.7 ± 0.4	**2.4***
Ca	**%**	0.6 ± 0.2	0.5 ± 0.1	**0.9**	1.1 ± 0.4	0.7 ± 0.1	**2.3***
P	**%**	0.4 ± 0.1	0.2 ± 0.1	**0.4**	0.9 ± 0.3	0.4 ± 0.1	**2.2***
Mg	**%**	0.2 ± 0.0	0.2 ± 0.1	**0.2**	0.3 ± 0.1	0.3 ± 0.1	**0.1**

*: $p < 0.05$.

Table 4
Seasonal variation in the organic nutrients (Mean ± SD) of *Ludwigia stolonifera* grown in polluted and unpolluted watercourses. EE: ether extract, CF: crude fiber, TP: total protein, NFE: nitrogen-free extract (soluble carbohydrate). R: belowground roots, S: aboveground shoots. Maximum and minimum values are underlined.

Season			Organic nutrient (%)				
			EE	CF	Ash	TP	NFE
Polluted canals	**Spring**	**R**	0.8 ± 0.1b	29.3 ± 2.5b	7.5 ± 1.1c	4.7 ± 0.6 cd	57.8 ± 12.9bc
		S	1.8 ± 0.3a	36.3 ± 3.9a	6.3 ± 0.5c	8.1 ± 1.7bc	47.3 ± 4.5 cd
	Summer	**R**	0.4 ± 0.1 cd	18.6 ± 3.4 cd	10.7 ± 0.5b	5.6 ± 1.2c	64.8 ± 4.3ab
		S	0.6 ± 0.3c	36.5 ± 4.2a	8.3 ± 0.8bc	13.9 ± 2.1a	40.6 ± 2.5d
	Autumn	**R**	0.3 ± 0.1d	16.3 ± 3.2 cd	12.4 ± 2.7a	4.6 ± 0.9d	66.3 ± 4.2ab
		S	0.7 ± 0.1b	25.5 ± 4.3bc	8.2 ± 1.8bc	11.4 ± 1.6ab	54.1 ± 1.5c
	Winter	**R**	0.2 ± 0.1d	15.8 ± 4.3d	7.3 ± 1.8c	3.1 ± 0.8d	73.6 ± 12.9a
		S	0.3 ± 0.1d	22.3 ± 4.8c	6.9 ± 0.5c	10.2 ± 2.8b	60.2 ± 11.9b
F-value			**29.1*******	**13.2*******	**7.2*******	**87.7*******	**11.3*******

Means with the same letters are not significant according to Duncan's test. ***: $p < 0.001$.

(12.4 and 73.6%) during autumn and winter, respectively, while the lowest EE, CF and TP (0.2, 15.8 and 3.1%) during winter. Additionally, significant differences in the estimated organic nutrients, except for ash content (of the roots), and those except for CF and ash content (of the shoots), were recorded between polluted and unpolluted canals (Fig. 3). Under pollution conditions, the water primrose EE showed significant increases from 0.2 to 0.4% in its root and 0.3 to 0.9% in the shoot. Likewise, NFE was increased from 60.3 to 65.6% in the root and from 47.1 to 50.6% in the shoot. However, the CF content decreased from 22.9 to 20.0% in the root and TP from 6.3 to 4.2% and 15.4 to 10.9% in the root and shoot, respectively,

3.5. Nutritive value

The estimation of water primrose plants' nutritive value revealed highly significant variations in all investigated elements (Table 5). The belowground parts had the highest amounts of total dissolved nutrients (TDN) (60.2%), as well as the highest digestible (DE), metabolized (ME) and net energy (NE) (3.2, 2.6 and 1.3 Mcal kg^{-1}, respectively) during winter, while the lowest digestible crude proteins (DCP) (0.8%) and GE (374.9 Mcal kg^{-1}) during spring and autumn, respectively. On the other side, the aboveground tissues of water primrose had the highest value of DCP (9.4%) and GE (428.8 Mcal kg^{-1}) during summer and spring; respectively, while the lowest DE, ME and NE (2.4, 2.0 and 1.0 Mcal kg^{-1}) in spring and summer. Moreover, there were no significant differences in most plants' nutritive values, except DCP in the root and DCP, and GE in the shoot, between polluted and unpolluted watercourses (Table 6). The values of DCP and GE in the root and shoot of water primrose collected from the unpolluted Nile were higher than those collected from the polluted canal.

4. Discussion

The nature of water and bottom sediment of aquatic ecosystems may reflect the intensity and type of pollution resulted from pollutant discharge (Eid et al. 2012). The water and sediment chemical characteristics showed significant differences between polluted and unpolluted watercourses. The high amounts of nutrients in

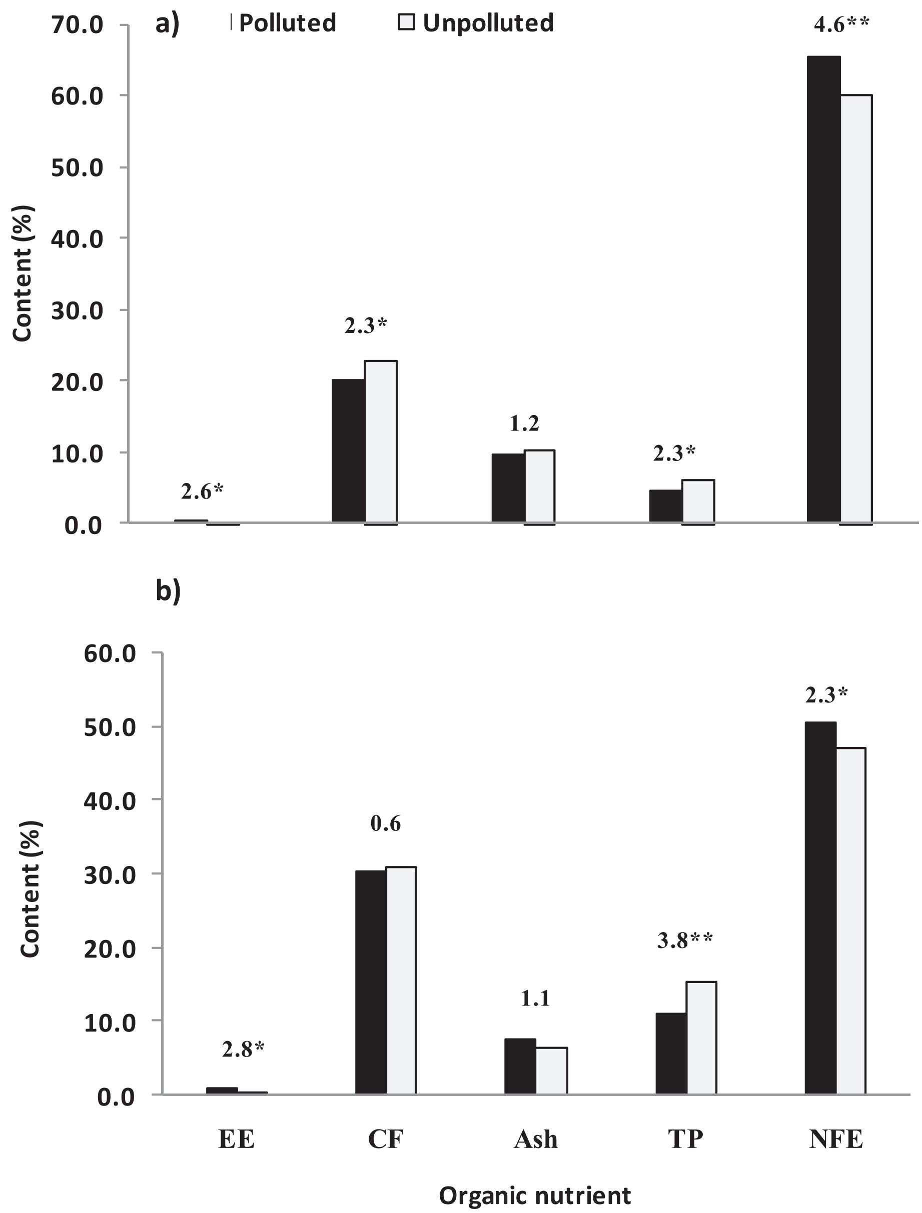

Fig. 3. Organic nutrient of the below- (a) and above-ground (b) tissues of *Ludwigia stolonifera* collected from polluted and unpolluted watercourses. T-values are provided. *: $p < 0.05$, **: $p < 0.01$.

Table 5
Seasonal variation in the nutritive value (Mean ± SD) of *Ludwigia stolonifera* grown in polluted and unpolluted watercourses. DCP: digestible crude protein, TDN: total digestible nutrients, DE: digestible energy, ME: metabolized energy, NE: net energy and GE: gross energy. R: belowground roots, S: aboveground shoots. Maximum and minimum values in the polluted canal are underlined.

Season			DCP %	TDN %	DE Mcal kg^{-1}	ME	NE	GE
Polluted canals	**Spring**	**R**	0.8 ± 0.5d	59.5 ± 3.6ab	2.6 ± 0.1c	2.2 ± 0.1b	1.1 ± 0.1b	406.9 ± 31.8b
		S	4.0 ± 1.5bc	57.9 ± 1.4bc	2.4 ± 0.1d	2.0 ± 0.1c	1.0 ± 0.1c	428.8 ± 25.6a
	Summer	**R**	2.8 ± 1.1c	58.6 ± 1.5bc	2.8 ± 0.2b	2.3 ± 0.1ab	1.2 ± 0.1ab	385.6 ± 32.3bc
		S	9.4 ± 1.9a	52.8 ± 1.3e	2.4 ± 0.1d	2.0 ± 0.1c	1.0 ± 0.1c	424.5 ± 13.7ab
	Autumn	**R**	1.1 ± 0.1 cd	59.3 ± 2.7ab	2.8 ± 0.2b	2.3 ± 0..1ab	1.2 ± 0.1ab	374.9 ± 16.3c
		S	7.1 ± 1.5b	54.6 ± 1.1de	2.7 ± 0.1bc	2.2 ± 0.1b	1.1 ± 0.1b	412.6 ± 7.6ab
	Winter	**R**	0.9 ± 0.1d	60.2 ± 3.6a	3.2 ± 0.6a	2.6 ± 0.1a	1.3 ± 0.1a	391.5 ± 9.9bc
		S	5.9 ± 2.6bc	55.2 ± 2.1 cd	2.8 ± 0.8b	2.3 ± 0.2ab	1.2 ± 0.1ab	411.1 ± 13.2ab
F-value			**87.7*****	**78.7*****	**8.1*****	**8.1*****	**8.1*****	**18.4*****

Means with the same letters are not significant according to Duncan's test. ***: $P < 0.001$.

Table 6
Nutritive value (Mean ± SD) of the different organs of *Ludwigia stolonifera* collected from polluted and unpolluted canals.

Nutritive value		Root		t-value	Shoot		t-value
		P	U		P	U	
DCP	%	1.1 ± 0.4	2.4 ± 1.1	**2.6***	6.6 ± 2.2	10.8 ± 2.3	**3.1***
TDN		59.4 ± 6.7	57.9 ± 0.8	**1.2**	55.1 ± 2.1	51.5 ± 1.7	**1.2**
DE	Mcal kg^{-1}	2.9 ± 0.2	2.7 ± 0.2	**1.3**	2.6 ± 0.2	2.6 ± 0.2	**0.4**
ME		2.3 ± 0.2	2.2 ± 0.1	**0.7**	2.1 ± 0.2	2.1 ± 0.1	**0.2**
NE		1.2 ± 0.1	1.1 ± 0.1	**0.9**	1.1 ± 0.2	1.1 ± 0.1	**0.2**
GE		389.7 ± 13.4	390.6 ± 41.7	**1.1**	419.2 ± 28.8	428.7 ± 34.3	**2.3***

*: $p < 0.05$.

the polluted canal may be attributable to the domestic, industrial, and agricultural drainage from the anthropogenic activities in the nearby area (Eid et al. 2010). The agricultural activities include irrigation and fertilization around the polluted sites, which could significantly increase the contents of inorganic elements and thus elevate nutrients level (Kiani et al., 2020; Wu et al., 2021). In addition, most of the investigated variables were concentrated in the sediment more than water. As stated by Schulz et al. (2003), sediments act as semi-permanent nutrient sinks and thus become sources of nutrients for aquatic ecosystems, since nutrient input to water occurs through escape from sediments.

The water primrose plants' highest biomass was attained during summer; then, it was significantly reduced to reach its lowest value during winter. This result coincided with those of Shaltout et al. (2010) on *Echinochloa stagnina*, Galal and Shehata (2016) on *Arundo donax,* and Galal et al. (2019b) on *Pistia startiotes*. The maximum biomass of water primrose was 512.6 g DW m^{-2} compared to 64.1 g DW m^{-2} of the same plant (Galal et al. 2019a) and 358.4 g DW m^{-2} recorded by Galal et al. (2019b). The reduction in the plant biomass during winter may be attributed to the shoot carbohydrates' translocation to the belowground parts at the plant senescence (Eid et al. 2020). Moreover, the water primrose's biomass in the unpolluted Nile was significantly higher than that in the polluted canal, which may be linked with higher salinity. According to Soetaert et al. (2004), plant biomass is lower in more salty areas. In addition, Sánchez et al. (2015) indicated a significant decline in the biomass of the giant reed under salt stresses. However, Galal et al. (2019a) attributed the decrease in water primrose's biomass to increased heavy metal concentration in the polluted canal. In the meantime, the belowground pools provide necessary amounts of nutrients for young stem growth in early spring, during which a reverse translocation occurred again to the shoot (Eid et al. 2020).

The ability of nutrient uptake by aquatic plants differed seasonally due to the change in water and sediment nutrient content in response to the seasonal changes in plant growth requirements following seasonal changes in biomass production (Manolaki et al. 2020). The above- and belowground organs of the water primrose exhibited significant seasonal variation in their inorganic nutrients. This result agrees with Klaus et al. (2011), who reported that plant nutrients varied according to the growing season and plant size. The water primrose accumulated the most investigated nutrients in its tissues in the growing season during summer. Following Vymazal (2020), the highest nutrient concentrations are collected in the plant tissues at the beginning of the growing season and then gradually decrease as plants mature and senesce. The primrose shoots accumulated higher N, P, Ca, and Mg contents than the root, which accumulated higher concentrations Na and K. Similar results were reported by Ruiz and Velasco (2010) and Eid (2012). Maddison et al. (2009) stated that the accumulation of nutrients depends on the nitrogen and phosphorus contents in the plant organs rather than plant biomass. Given this point, the present study recorded high concentration of N during winter associated with the lowest plant biomass. Similar results were postulated by Irfan (2014) that the increase of N concentrations improve the nitrogen storage in plant tissues and negatively affect the plant biomass. In addition, Bignal et al. (2008) stated that the nitrogen in tissues might not benefit plant growth.

For efficient removal of nutrients from polluted water, it is crucial to harvest the water primrose aboveground shoots before leaves reach senescence, and nutrients are translocated to other plant parts (Eid et al. 2020). The present investigation recognized the ideal time of harvesting primrose plants to remove the highest nutrients content from the polluted canal. Early season mowing stimulates new shoot emergence (Nikolaidis et al. 1996), consequently accumulating more nutrient contents. Based on the present investigation results, the summer season is the ideal time to harvest water primrose for removing the maximum nutrient for restoring eutrophic watercourse. This result may be attributed to the highest nutrient accumulation, especially N and P, associated with the highest plant biomass during this season. According to Eid et al. (2020), the optimum time for harvesting the common reed for treating eutrophication in Lake Burullus during spring at the highest nutrient contents as well as the highest biomass. However, Tanaka et al. (2017) reported that harvesting the aboveground biomass during the growing seasons might pose a decline in the belowground parts' reserves, which negatively affects the next shoot growth. In eutrophic watercourses, aquatic plants may release more nutrients to the surroundings rather than uptake them, but this is mainly during winter senescence if biomass is not harvested in summer (Geurts et al. 2020).

The present study reported the decrease in crude fibers and total proteins, while the increase in soluble carbohydrates content in the below- and aboveground tissues of water primrose under pollution stress. John et al. (2009) attributed the decrease in protein content in polluted watercourses to the photosynthesis inhibition or respiration enhancement. However, Costa and Spitz (1997) attributed this to heavy metal stress conditions. Moreover, Abdel Latef et al. (2020) reported increased carbohydrate content under salt stress of polluted conditions, which aid plants in preserving water balance by turgor pressure maintainance and osmotic stress resistance. Our results showed that the aboveground shoots had higher crude fibers and total proteins in the water primrose's polluted canal than the belowground parts. According to Heneidy (2002), crude protein and crude fibers are considered an indicator of the nutritional value of grazing animals' nutritional value. Therefore, the aboveground organs are more suitable as animal feed than the belowground parts.

The minimum protein content required for animal feed are 6–12%, which depends mainly on the animal species (Shaltout et al. 2016). Summer biomass can be used to produce fiber-rich fodder (Geurts et al. 2020), whereas the biomass should be harvested when the protein content is highest (Pijlman et al., 2019). In spring, autumn, and winter seasons, the protein content in the grazeable parts (shoots) of the water primrose was within the range, while in summer, it was higher than the minimum requirement for the maintenance of animals. This content agrees with some rough foods' scale of the protein content (2.7–13.4%: Shoukry 1992). The same is right regarding ash content (1.3–23.1%). The high protein content and minerals in the aboveground shoots of the water primrose may increase the growth and production of cattle's meat and milk. Ibewiro et al. (2000) reported that some forage herbs might limit the growth and production of cattle milk and meat because of their relatively low crude protein contents and some minerals, compared to browse species. The lipids (ether extract) take in plants' structure and use in its metabolism (Shaltout et al. 2010). Chapin et al. (1986) showed that lipids are insignificant as energy sources in some plants. Lipids of the water primrose's shoots lay within the scale of some rough fodder constituents (0.5–3.1%: Shoukry 1992). Moreover, the crude fiber was higher than that of *Trifolium alexandrinum* (21.5%: Chauhan et al. 1980).

The total digestible nutrients (TDN) are a suitable measure of the feed energy available to animals only after the digestion losses have been removed (El-Beheiry 2009). The mean value of TDN of the shoots of the water primrose meets the diet requirements of sheep (61.7%: NRC 1975) and breeding cattle (50.0%: NRC 1984). In addition, the mean value of digestible energy meets the amount (2.7 Mcal kg^{-1}) required by sheep (NRC 1985). The mean annual value of the aboveground shoots' metabolized energy was 2.1 Mcal kg^{-1}, which approximated the requirement of sheep and breeding cattle (NRC 1985, 1984). It appears that the nutritive value of the aboveground shoots of the primrose plants lie within the range of nutritive value of dairy cattle (NRC 1978), sheep (NRC 1975), beef cattle (NRC 1984), and goat (NRC 1981).

5. Conclusion

The water primrose plants' highest biomass was attained during summer; then, it was significantly reduced until winter reached its lowest value. The plant accumulated most of the investigated nutrients (except Na and Mg) in the shoots rather than the root. The water primrose can confiscate large amounts of nutrients in its biomass; consequently, it can be used for nutrient elimination from polluted water and sediment. Summer is the ideal season to harvest water primrose plants for removing the maximum nutrient for restoring eutrophic watercourse. This result may be attributed to the highest nutrient accumulation, primarily N and P, associated with the highest plant biomass during this season. The aboveground shoots of water primrose's nutritive values lie within the range of nutritive value of sheep, goat, dairy, and beef cattle. The total protein, lipids, and crude fibers of the aboveground parts of water primrose support this plant as a rough forage.

Authors contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Tarek Galal, and Hatim Al-Yasi. The first draft of the manuscript was written by Mona Abu Alhmed and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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