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The ability of *Typha latifolia* L. to accumulate nutrients from rural ponds

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ABSTRACT

Eutrophication of small ponds poses an important problem in rural areas as there is an increased risk of nutrient inflow. The accumulation properties of some macrophytes create an opportunity to limit the outflow of waste from agricultural activities to the catchment area. The aim of the study was to assess the suitability of *Typha latifolia*, which by collecting and accumulating N, P, K, Mg and Ca can improve water quality. The research covered 10 ponds located in northern Poland. The obtained test results indicate statistically significant differences ($p < 0.05$) between the water ponds in the content of P and Mg in rhizomes and roots and Mg in the leaves of *T. latifolia*. The lack of statistically significant differences in the case of N, K and Ca indicates a strong impact of species characteristics on the accumulation capacity of this macrophyte in relation to nitrogen, potassium, and calcium. It was found that the accumulation capacity of *T. latifolia* significantly shaped the content of organic matter in bottom sediments and their pH. The accumulation properties of *T. latifolia* differed between groups A and B, with organic matter content ranging from 28.1% to 37.9% (group A) and from 4.6% to 16.3% (group B). The reaction of bottom sediments significantly influenced the content of Mg and Ca in leaves (group A) and the content of P (in leaves, rhizomes and roots), K (in leaves and rhizomes) and Ca (in leaves, rhizomes and roots) in group B water ponds. This variation confirms that the accumulation capacity of *T. latifolia*, dependent on the species and modified by the physicochemical properties of bottom sediments, significantly limit the outflow of nutrients to the catchment.

Keywords: Bottom sediments; Accumulation; Bioconcentration factor; Principal components analysis; Hierarchical cluster analysis

1. Introduction

In recent years, in Poland, there has been intense pressure from modern techniques of agriculture intensification and the associated chemisation of arable fields [1,2]. Therefore, small (0.2–1.0 ha) ponds adjacent to crops are exposed to the inflow of pollutants. Biogens pose a significant threat to the ponds, entering them along with surface runoffs from arable fields and groundwaters [3–5]. As a result, both waters, bottom sediments and coastal vegetation of ponds remain under the influence of various anthropogenic factors depending on the nature of the catchment area [6,7]. Elements and chemical compounds entering the ponds undergo accumulation and biotransformation processes [8]. They are often immobilized in bottom sediments for a long time [9,10]. Coastal plants play a significant role in the quality of surface waters and the functioning of ponds. Many components accumulated in bottom sediments are available to macrophytes, which take up and accumulate them in leaves, rhizomes and roots [11–13]. One of the most important species, often found in ponds in northern Poland, is *Typha latifolia* L. The plant forms dense cattail rushes which, through the extensive system of rhizomes and roots, constitute an efficient barrier to incoming pollutants [14–17]. It mainly inhabits standing, fertile waters, not exceeding a depth of 2 m. It stabilizes bottom sediments, produces oxygen dissolved in water, participates in the circulation of nutrients and takes part in the self-cleaning processes of waters. Depending on the size

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of the pond and the degree of its eutrophication, *T. latifolia* exhibits different accumulation properties in relation to many components. Nutrients taken by roots and rhizomes and then accumulated in various organs, are crucial for the growth and development of the plant and constitute a significant element of the natural cycle [17–23]. However, with strong contamination of water and bottom sediments with biogens, many nutrients can be taken up by vegetation in a passive manner [16], and their concentrations in tissues can exceed the content of these compounds in the surrounding environment [24–26]. Any disturbance in the development of macrophytes caused by the inflow of pollutants poses a threat to the entire ecosystem, including human health and life [27]. Among many solutions aimed at inhibiting the eutrophication process of small ponds, high hopes are placed in phytoremediation, that is, the treatment of the environment with the help of plants. *T. latifolia* has a beneficial and multi-level effect on the condition of the entire reservoir because the accumulated nutrients are temporarily excluded from the circulation in the ponds and contribute to the reduction of pollution of these ecosystems. Therefore this study aim to assess suitability potential of *T. latifolia* as an option for water treatment in rural ponds under conditions of extreme nutrient effect. An innovative approach, related to the assessment of the accumulation capacity of *T. latifolia* interpreted depending on the physicochemical properties of bottom sediments, allowed for accurate recognition of the accumulation properties of this macrophyte.

The aim of the study was: (i) to identify the factors determining the content of nutrients accumulated in bottom sediments and in leaves, rhizomes and roots of *T. latifolia* of small ponds in rural areas in northern Poland, (ii) to compare the bioconcentration coefficients N, P, K, Mg and Ca in the organs of *T. latifolia* and (iii) to assess the accumulation ability of *T. latifolia* and the suitability of this macrophyte to improve the quality of water in ponds in rural areas.

2. Materials and methods

2.1. Research area

The research was carried out in Northern Poland, in the zone of varied young glacial landscape, characterized by numerous glacial ponds with an area of less than 1 ha. Ten ponds located in rural areas, at a distance not exceeding 15 km from the city of Słupsk (Table 1).

Weather conditions in the studied area are shaped under the influence of the Baltic Sea. They were characterized by relatively cool springs and summers, warm autumns and mild winters. The warmest month of the year was July, and the coldest month was February. The average annual air temperature was +7°C, and its humidity was 88.7% [28]. In the studied area, the average annual sum of precipitation amounted to 600 mm, and south–west and west winds prevailed [29].

The water ponds selected for testing had diverse surroundings. In the immediate vicinity of Bruskowo Wielkie (BW), Kusowo (KU), Reblino (RE), Runowo Sławieńskie (RS) and Swołowo (SW) there were rural farm buildings, farmland, agricultural wastelands and meadows; near Bierkowo (BI), Głobino (GŁ) and Niewierowo (NI) ponds – residential buildings, and Siemianice (SI) and Kobylnica (KO) ponds – farm buildings, meadows and forests (Fig. 1).

2.2. Sampling procedure and the analyzes used

Bottom sediment samples from a depth of 0–15 cm and leaves, rhizomes and roots of *T. latifolia* were collected for testing in the summer, from each pond, in three repetitions. A total of 120 samples were subjected to chemical analyses, including 30 samples of bottom sediments and 30 samples of leaves, rhizomes and roots. After transport to the laboratory, the samples of bottom sediments were dried at 65°C for 48 h, ground in a mortar and then sieved through a 1 mm × 1 mm sieve. In the bottom sediments, the active acidity (pH in an aqueous solution, in a weight ratio of 1:2.5) was determined by the potentiometric method (CPI 551 Elmetron, Poland). Next, the organic matter content (OM) was determined by roasting bottom sediments in a muffle furnace at 550°C (FCF 7SP, Czylok, Poland). The plant samples were subject to preliminary preparation, which consisted in purifying the residual sediments by rinsing them in deionized water. Then the plants were dried at 65°C for 48 h and homogenized in a laboratory grinder (A11 basic IKA, Germany). Until the completion of chemical analyses, the samples were stored in tightly closed polyethylene bags. Nitrogen was determined by the Kjeldahl method (K-350 Büchi, Switzerland), after mineralization of samples (plants – 0.5 g, bottom sediments – 1 g) in

Table 1
Location, geographical coordinates and use of the land around the ponds

Location	Geographical coordinates	Use of the land in the catchment
Bierkowo (BI)	54°28′ N 16°55′ E	Rural farm buildings
Bruskowo Wielkie (BW)	54°29′ N 16°54′ E	Rural farm buildings
Głobino (GŁ)	54°26′ N 17°06′ E	Fields near the wasteland
Kobylnica (KO)	54°26′ N 16°59′ E	Fields near wasteland and forest
Kusowo (KU)	54°26′ N 17°40′ E	Rural farm buildings
Niewierowo (NI)	54°29′ N 17°20′ E	Rural farm buildings, near the fields
Reblino (RE)	54°25′ N 16°54′ E	Rural farm buildings
Runowo Sławieńskie (RS)	54°24′ N 16°54′ E	Rural farm buildings, near the fields and forest
Siemianice (SI)	54°30′ N 17°03′ E	Rural farm buildings, near the forest
Swołowo (SW)	54°28′ N 16°50′ E	Rural farm buildings, near the fields

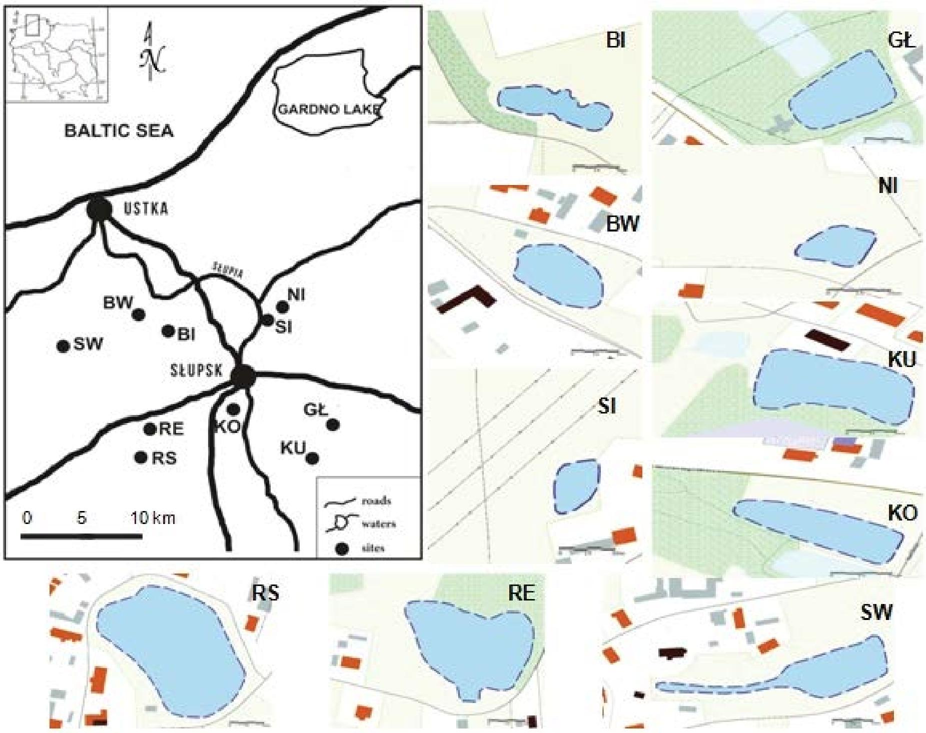

Fig. 1. Location of rural ponds and characteristics of their catchments (BI – Bierkowo, BW – Bruskowo Wielkie, GŁ – Głobino, KO – Kobylnica, KU – Kusowo, NI – Niewierowo, RE – Reblino, RS – Runowo Sławieńskie, SI – Siemianice, SW – Swołowo).

a mixture of 10 mL of 98% H_2SO_4 and 2 mL of 30% H_2O_2. To determine P, K, Mg and Ca, plant samples (0.5 g) and bottom sediments (0.5 g) were digested in a mixture of 8 mL of 65% HNO_3 and 2 mL of 30% H_2O_2 in a microwave mineralizer (Ethos Easy, Milestone connect). After mineralization, the samples were topped up with deionized water to a volume of 50 mL and 25 mL, respectively (Hydrolab HLP10, Poland). The P content was determined using the spectrophotometric method with ammonium molybdate (UV-VIS, Hitachi U-5100, Japan) at a wavelength of 700 nm. The content of K, Mg and Ca was determined by atomic absorption spectrometry (ICE 3000, Thermo Scientific, USA) in an acetylene-oxygen flame at the following wavelengths: K – 769.9, Mg – 202.6 and Ca – 422.7 nm. The spectrometer was calibrated on the basis of original Fluka Analytical Standards solutions (KGaA, 1 g/1,000 mL, K – BCBN 1838V, Mg – BCBD 7278, Ca – BCBM 8587V). The K, Mg and Ca concentration in the samples was calculated using the following formula:

$$C = \frac{A \cdot V}{W} \tag{1}$$

where A – AAS reading; C – Concentration of K, Mg, Ca (mg/kg); W – Weight of the samples; V – Volume of diluted solution.

The quality control of the analytical procedures was carried out by analyzing the standard certified reference material (aquatic plants, CRM 060, Belgium). The error associated with the analysis of certified materials did not exceed the range deemed permissible (±3%).

2.3. Statistical analysis

Calculations and figures were made in Statistica 13.3. The distribution of data was checked using the Shapiro–Wilk test. Standard deviation (SD) and coefficient of variation (CV) of variables were calculated. A standard deviation is a statistical measure that gives the dispersion of a dataset relative to its mean and is calculated as the square root of the variance. The standard deviation takes a value greater than the average when the data set is highly diverse and there is no normal distribution. Then, there is a non-Gaussian distribution of variables (Fig. 2 and Tables 2 & 3). The larger the standard deviation value, the more distant the observations are from the mean value and indicate a strong diversification of the variable [30]. The Kruskal–Wallis test was used to demonstrate statistically significant differences between the analysed parameters in bottom sediments, leaves, rhizomes and roots. The ability of *T. latifolia* to absorb and accumulate nutrients from the bottom sediments was evaluated using the bioconcentration factor (BCF) [31]. The BCF value is calculated as the ratio of the concentrations of nutrients in the plant and their concentrations in bottom sediment:

$$\text{BCF} = \frac{C_{\text{leaves(rhizomes,roots)}}}{C_{\text{bottom sediments}}} \tag{2}$$

where $C_{\text{leaves(rhizomes, roots)}}$ – nutrients content in leaves, rhizomes or roots (mg/kg); $C_{\text{bottom sediments}}$ – nutrients content in bottom sediments (mg/kg).

In order to identify the factors determining the content of nutrients in bottom sediments and in leaves, rhizomes and

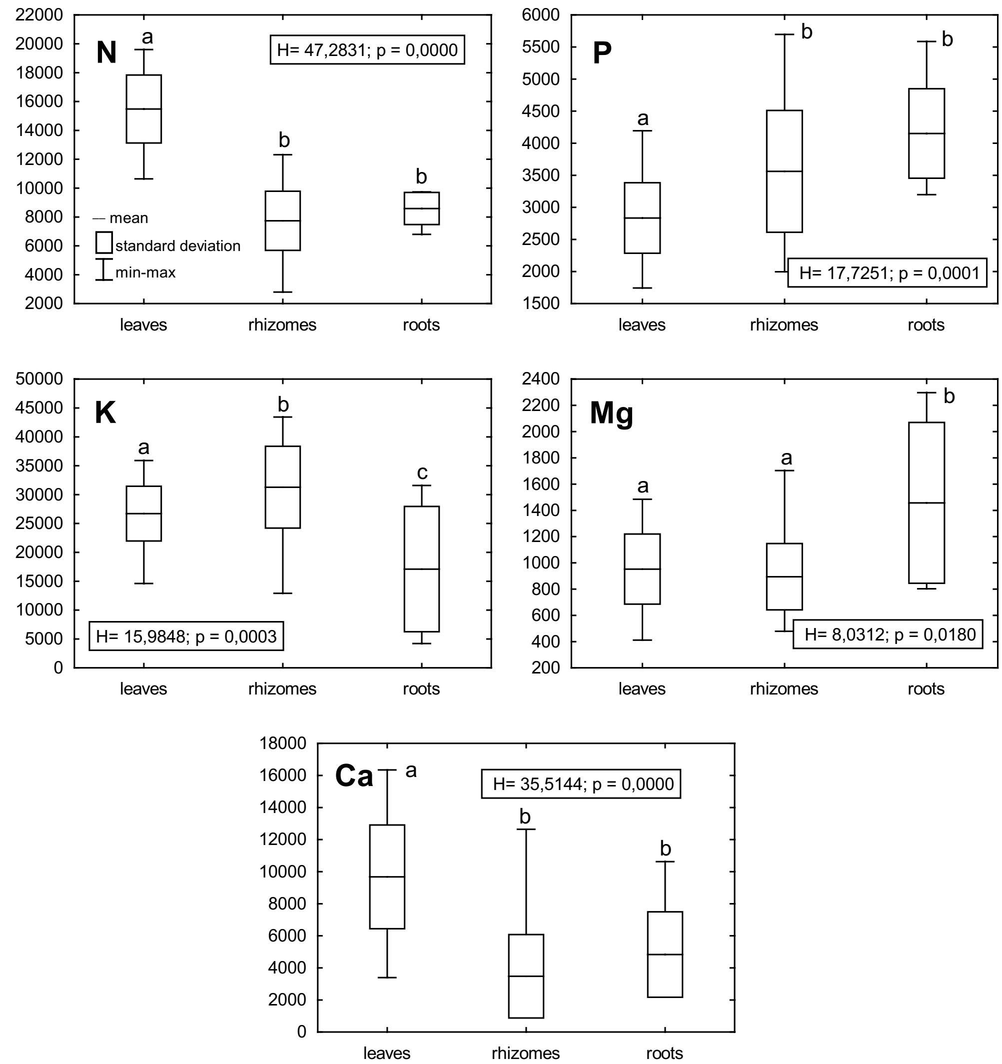

Fig. 2. Nutrients content (mg/kg) in *Typha latifolia* organs in rural ponds with Kruskal-Wallis's test results. The same letter – no statistical differences.

Table 2
Physicochemical properties of bottom sediments and their statistical characteristic

Location	pH		OM, %			
	Range	Median	Range	Median	Mean ± SD	CV, %
Bierkowo (BI)	6.2–6.5	6.4	1.8–8.6	3.3	4.6 ± 3.5	77.6
Bruskowo Wielkie (BW)	6.0–6.5	6.4	16.5–50.9	16.7	28.1 ± 19.9	70.8
Głobino (GŁ)	7.3–8.5	7.7	2.3–10.7	9.6	7.5 ± 4.6	61.1
Kobylnica (KO)	5.9–6.6	6.1	5.8–25.3	17.9	16.3 ± 9.9	60.5
Kusowo (KU)	6.4–7.9	6.7	3.3–12.0	9.5	8.3 ± 4.5	54.3
Niewierowo (NI)	6.3–6.7	6.6	11.3–51.9	25.8	29.7 ± 20.6	69.2
Reblino (RE)	4.8–6.1	5.9	16.5–77.8	17.8	37.4 ± 35.0	93.8
Runowo Sławieńskie (RS)	5.6–6.2	6.1	20.1–47.0	46.5	37.9 ± 15.4	40.6
Siemianice (SI)	7.2–7.3	7.2	7.4–72.9	8.9	29.8 ± 37.4	125.7
Swołowo (SW)	4.3–6.3	6.1	27.3–52.5	30.5	36.8 ± 13.7	37.3
Range	4.3–8.5	–	1.8–77.8	–	–	–

SD – standard deviation, CV – coefficient of variation.

Table 3
Nutrients accumulation in bottom sediments with Kruskal–Wallis's ($p < 0.05$) test results

Location		N	P	K	Mg	Ca
		Mean (mg/kg) ± SD				
Bierkowo (BI)		1026.7 ± 450	1,318.8 ± 260	1,789.4 ± 713	866.4 ± 249	1,068.3 ± 141
Bruskowo Wielkie (BW)		3,570.0 ± 1,881	1,312.2 ± 197	2,653.8 ± 436	1,183.5 ± 287	493.6 ± 74
Głobino (GŁ)		2,566.7 ± 1,012.8	1,161.9 ± 328	3,069.4 ± 208	3,023.9 ± 429	19,359.2 ± 1,410
Kobylnica (KO)		4,060.0 ± 1,787	1,077.6 ± 162	2,896.9 ± 849	2,161.3 ± 1,150	4,945.9 ± 804
Kusowo (KU)		2,100.0 ± 1,009	1,445.3 ± 714	1,021.8 ± 277	773.4 ± 98	2,646.3 ± 217
Niewierowo (NI)		5,693.3 ± 2,701	1,511.2 ± 566	2,302.5 ± 989	961.2 ± 255	369.1 ± 49
Reblino (RE)		4,806.7 ± 3,119	1,458.5 ± 961	1,103.2± 619	566.9 ± 333	1,433.3 ± 148
Runowo Sławieńskie (RS)		8,680.0 ± 2,831	1,425.5 ± 716	3,373.3 ± 802	1,486.8 ± 253	1,433.3 ± 148
Siemianice (SI)		1,493.3 ± 530	657.1 ± 328	239.2 ± 56	351.1 ± 216	10,335.2 ± 1,509
Swołowo (SW)		8,540.0 ± 4,146	1,790.6 ± 681	3,599.9 ± 1,901	1,289.2 ± 525	251.3 ± 14
Mean		4,277.2 ± 3,263	1,315.9 ± 546	2,204.9 ± 1,294	1,266.4 ± 867	4,045.7 ± 813
Minimum		700.0	408.1	168.5	153.2	34.1
Maximum		12,880.0	2,562.9	5,445.0	3,727.5	29,080.0
CV, %		76.3	41.5	58.7	68.5	201.8
Kruskal–Wallis's	*H*	20.1939	7.8043	21.1118	23.0645	14.005
test	*p*	***0.0168***	0.5540	***0.0122***	***0.0061***	0.1221

SD – standard deviation, CV – coefficient of variation, bold–italic values – statistically significant differences.

roots of *T. latifolia* of ponds, principal component analysis (PCA) was used after standardized varimax rotation. The applied rotational strategy makes the structure of factors easier, which enables simple and more reliable interpretation. In the presented case study factor loadings higher than 0.7 were analyzed.

The accumulation ability of *T. latifolia* relative to nutrients was compared using the Ward method. The presented dendrogram illustrates the hierarchical structure of a set of objects (ponds) with decreasing similarity between them. The Ward method uses a variance approach to estimate the distance between clusters [32]. From the samples of leaves, rhizomes and roots of *T. latifolia*, two groups (A and B) with similar accumulation abilities were selected. Subsequently, each group was separately correlated with the physico-chemical properties of the bottom sediments of the respective water ponds. Correlation coefficients show the strength (absolute value) and direction (sign) of the interdependence of two features of the analysed cluster. The Spearman correlation coefficient value is in the closed interval [–1,1]. The closer it is to the ends of this range, the stronger the correlation between the features [30].

3. Results and discussion

3.1. Physicochemical properties of bottom sediments

The tested bottom sediments showed different properties, at pH values from 4.3 (SW) to 8.5 (GŁ). Acidic reaction was demonstrated by sediments in ponds in BI, BW, KO, NI, RE, RS and SW, neutral in SI and KU, and an alkaline reaction was found in the case of GŁ. The content of organic matter (OM) varied strongly between ponds, as evidenced by the wide range of its occurrence, from 1.8% (BI) to 77.8% (RE) (Table 2). Both pH and organic matter content are very important parameters as bioavailability of nutrients and impurities for plants depends on them [33]. Organic substances accumulate more frequently in the vicinity of macrophyte habitats [34]. Many chemical compounds show increased mobility in the acidic environment as they occur then in soluble forms, bioavailable for plants [35].

The content of nutrients in the sediments of the tested ponds varied. However, statistically significant differences were found only in the case of N (p = 0.0168), K (p = 0.0122) and Mg (p = 0.0061) (Table 3). The largest amounts of nitrogen were found in ponds in RS (8,680.0 mg/kg) and SW (8,540.0 mg/kg). Bottom sediments in BI (1,026.7 mg/kg) showed the lowest N content. Within the tested ponds, the nitrogen content variation was 76.3%. In the case of phosphorus, the variation was much lower (41.5%). The smallest amounts of P were found in the bottom sediments in SI (657.1 mg/kg) while the largest in SW (1,790.6 mg/kg). Bottom sediments were also characterized by a varied content of potassium, magnesium and calcium. The largest amounts of K were found in the bottom sediments in SW (3,599.9 mg/kg) and GL (3,069.4 mg/kg), Mg in KO (2,161.3 mg/kg), and Ca in GL (19,359.2 mg/kg). The CV for K in the sediments of the tested ponds was 58.7%, for Mg 68.5%, and for Ca 201.8%.

The physicochemical properties of bottom sediments result primarily from the natural and anthropogenic conditions prevailing in the catchment [36]. Most of the surveyed ponds were located close to farm buildings and agricultural fields, where mineral fertilizers rich in N, P, K, Mg and Ca were regularly used. Inflowing biogenic substances pose a significant risk to the growth in the fertility of ponds, as they increase the risk of eutrophication. The evidence is the relatively high content of nitrogen and phosphorus in bottom sediments (Table 3) in most of them (RS, SW, NI, RE, KO, KU). Comparable amounts of N and P were shown in the studies by Klink et al. [11]. High content of Ca in bottom sediments may affect the increase in pH and weakening of P absorption by plants. With neutral or alkaline reaction, phosphorus compounds are practically non-absorbable to plants [37]. The highest bioavailability of N compounds for plants is observed at pH 6.0–8.0, P at pH = 5.0–7.0, K at pH = 6.0–10.0, and Mg and Ca at pH = 6.5–8.5 [37–39], and it is favoured by optimal moisture in water ponds. Bottom sediment is an underestimated factor affecting the efficiency of nutrient removal by plants [13,40].

3.2. Nutrients content in T. latifolia organs

The content of nutrients in *T. latifolia* varied depending on the organ as well as on the pond. N and Ca dominated in leaves, K in rhizomes, and P and Mg in roots (Fig. 2). The nitrogen content remained on average at 15,484.0 mg/kg in leaves, 7,736.0 mg/kg in rhizomes and 8,589.6 mg/kg in roots. The largest amounts of N were shown by the organs of *T. latifolia* in ponds in GŁ and SI.

In the case of phosphorus, the average content in leaves was 2,834.7 mg/kg, in rhizomes 3,561.7 mg/kg, and in roots 4,152.1 mg/kg (Fig. 2). The K content ranged from 14,606.7 mg/kg (KO) to 35,906.7 mg/kg (KU) in leaves, from 12,913.3 mg/kg (BW) to 43,433.3 mg/kg (NI) in rhizomes and from 4,210.3 mg/kg (KO) to 31,583.3 mg/kg (SI) in roots. The average Mg content was 952.3 mg/kg in leaves, 894.5 mg/kg in rhizomes and 1,457.1 mg/kg in roots. A slightly different distribution of values was found in the case of Ca. The largest amount of this element was found in leaves (9,676.3 mg/kg) and roots (4,833.0 mg/kg), slightly less in rhizomes (3,476.7 mg/kg). Most Mg and Ca were accumulated by *T. latifolia* organs in ponds in KO and SI.

Statistically significant differences in the content of N (p = 0.0000), P (p = 0.0001) and Ca (p = 0.0000) between aerial (leaves) and underground organs (rhizomes, roots) of *T. latifolia* and of K (p = 0.0003) and Mg (p = 0.0180) between rhizomes and roots were demonstrated (Fig. 2). A comparison of the distribution of nutrients in leaves, rhizomes and roots of *T. latifolia* between 10 ponds (Kruskal–Wallis test) showed statistically significant differences in the content of P in rhizomes and Mg in leaves at $p < 0.05$. This slight variation indicates a strong influence of *T. latifolia* species features determining the accumulation abilities in relation to nutrients [41].

The amount of nutrients taken by plants depends to a large extent on the demand for individual components and on the properties of bottom sediments [35]. *T. latifolia* was generally characterized by a good supply of N, P, Mg and Ca and an excessive content of K concerning the physiological demand (2,000–18,000 mg/kg) of most plant species [42]. Plants absorb nitrogen mainly in the form of ammonium and nitrate ions. *T. latifolia* shoots developing on sediments of neutral or alkaline reaction are willing to uptake nitrate ions, and those growing on acid sediments prefer ammonium ions. Unlike nitrogen, phosphorus shortens the growing season of plants and stimulates the development of generative organs. Potassium is often taken up by plants in large quantities [37], which in particular concerns aquatic species and other plants occurring in areas with high groundwater levels [4,16,43]. Potassium compounds, due to their good solubility, release K^+ ions, which are then taken up by plants in excess, very often exceeding the nutritional requirements [37,41]. The amount of calcium and magnesium absorbed by plants depends on the content of potassium ions and on the pH of bottom sediments. Calcium is less absorbable by plants than potassium, while magnesium is less bioavailable than potassium and calcium [44]. The accumulation abilities of *T. latifolia* depended strictly on the physicochemical properties of bottom sediments in ponds.

The relationships between nutrients were arranged in the following decreasing series: in leaves: K > N > Ca > P > Mg and in rhizomes and roots: K > Ca > N > P > Mg, which confirms their ability to absorb [44]. Similar relationships between the content of nutrients in *T. latifolia* leaves were observed by Klink et al. [11], conducting research in the Sławskie Lake District.

3.3. Bioconcentration factors

The mutual relations between the nutrients analysed in leaves, rhizomes and roots of *T. latifolia* and in bottom sediments were compared using the bioconcentration factor (BCF). BCF values >1 indicate that the component is absorbed from the bottom sediments. The highest BCF values concerned Ca and K, and the lowest Mg (Table 4). The values of BCF for nitrogen observed in leaves (6.6) were twice higher than in rhizomes (3.4) and roots (3.1). In the case of P and K, higher BCF values were found in roots (5.4 and 40.9, respectively) than in rhizomes and leaves. The lowest values of the Mg bioconcentration factor concerned leaves (1.3) and roots (1.9). The highest BCF values for Ca were found for leaves (43.7) and roots (41.4), and in the case of K – for roots (40.9) and rhizomes (27.3). The calculated BCF values indicate that *T. latifolia* absorbs nutrients from bottom sediments, following the downward trend: Ca > K > N > P > Mg. These data indicate that the value of the bioconcentration factor is dependent on the bioavailability of the absorbed component [37,45] and typical for the species [46].

3.4. Principal component analysis

In order to identify the factors determining the content of nutrients accumulated in bottom sediments and in leaves, rhizomes and roots of *T. latifolia*, the PCA was used. With the principal components method, 2 main factors explaining a total of 73.3% of variance were distinguished.

Table 4
Bioconcentration factor values in *Typha latifolia* organs

	Bioconcentration factor		
	Leaves/bottom sediment	Rhizomes/bottom sediment	Roots/bottom sediment
N	6.6	3.4	3.1
P	2.6	3.1	5.4
K	24.7	27.3	40.9
Mg	1.3	1.0	1.9
Ca	43.7	29.4	41.4

The first factor (FC1) was created by N, P, K and was characterized by high, positive values of factor loadings (0.78, 0.85 and 0.91, respectively). The second factor (FC2) grouped Mg (–0.75) and Ca (–0.85) with high, negative factor loadings (Table 5).

The relationships between FC1 (N, P, K) and FC2 (Mg, Ca) factors for bottom sediments, leaves, rhizomes and roots are presented in the form of a categorized scatter plot (Fig. 3). The distribution of green points in the upper right quadrant of the graph confirms a much greater abundance of N, P, K, Mg and Ca in leaves, compared to other samples. Bottom sediments (black points) of several ponds were characterized by significant abundance in Mg and Ca and low content of N, P and K compared to leaves, rhizomes and roots. The presented content of nitrogen, phosphorus and potassium compounds in bottom sediments is the result of intensive uptake by vegetation and leaching to waters. Ca and Mg compounds due to weaker solubility compared to N and K compounds [37], were accumulated in bottom sediments for a longer time.

Table 5
Results of principal component analysis with normalized varimax rotation

Nutrient	First factor	Second factor
N	***0.78***	–0.28
P	***0.85***	0.16
K	***0.91***	0.15
Mg	–0.25	***–0.75***
Ca	0.18	***–0.85***
Output value	2.26	1.41
Participation, %	0.45 73.3%	0.28

Factor loading levels higher than 0.7 are in bold–italic.

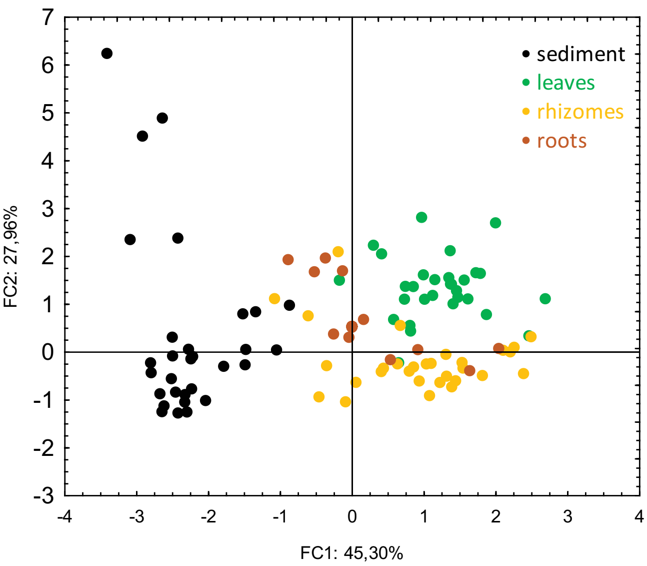

Fig. 3. First factor (N, P, K) vs. second factor (Mg, Ca) in *Typha latifolia*.

3.5. Hierarchical cluster analysis

On the basis of nutrients accumulated in leaves, rhizomes and roots, a similarity diagram of the accumulation abilities of *T. latifolia* in the tested ponds was prepared (Fig. 4). The separated groups: A and B, indicate similar accumulation abilities of *T. latifolia* in ponds in BI, BW, KO, SI, RE, RS, and in GŁ, KU, NI, SW.

In group A, there were ponds in which *T. latifolia* grew on the bottom sediments containing from 28.1% to 37.9% of organic matter. In the bottom sediments of group B, the content of organic matter was significantly lower and ranged from 4.6% to 16.3% (Table 2).

Then, in separated groups A and B, Spearman's correlation coefficients between the nutrient content in *T. latifolia* and the physicochemical properties of the bottom sediments of a given group were calculated (Table 6).

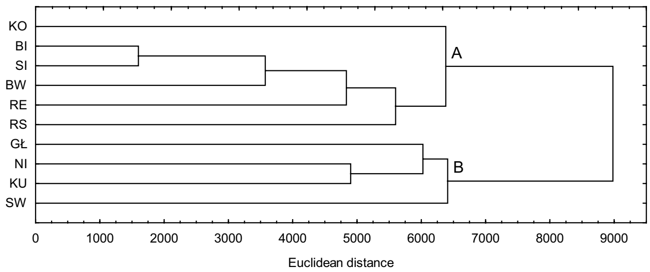

Fig. 4. Different accumulation properties of *Typha latifolia* depending on the bioavailability of nutrients in the ponds.

Table 6
Spearman's correlation coefficients ($n = 30$, $p < 0.05$) characterizing the relations between the nutrient content in *Typha latifolia* and the physicochemical properties of bottom sediments in group A and B

		N	P	K	Mg	Ca
		Leaves (■ green, □ green), Rhizomes (■ yellow, □ yellow), Roots (■ red, □ red)				
		Group A: BI, BW, KO, RE, SI, SW				
pH	Bottom sediments	–	–	–	■ green	■ green
OM		–	■ green	■ green	–	–
N		–	–	–	–	□ green
P		■ yellow ■ red	–	■ green ■ yellow ■ red	□ green □ yellow □ red	□ green
K		–	■ yellow ■ red	■ yellow ■ red	■ yellow ■ red	□ green
Mg		–	–	–	■ green ■ yellow ■ red	–
Ca		–	□ yellow □ red	–	■ green	–
		Group B: GŁ, KU, NI, SW				
pH	Bottom sediments	–	■ green ■ yellow ■ red	■ green □ yellow	–	■ green ■ yellow ■ red
OM		□ green □ yellow □ red	□ green	□ green ■ yellow ■ red	–	□ yellow □ red
N		□ green □ yellow □ red	□ green □ yellow □ red	□ green □ yellow	–	–
P		–	–	–	–	–
K		–	–	□ green	□ green	–
Mg		■ green ■ yellow ■ red	■ green	–	■ yellow ■ red	■ yellow ■ red
Ca		■ green	■ green	–	■ yellow ■ red	■ yellow ■ red

■ green, ■ yellow, ■ red – positive correlations, □ green, □ yellow, □ red – negative correlations.

The reaction of bottom sediments significantly affected the content of Mg and Ca in leaves (group A) and the content of P (in leaves, rhizomes and roots), K (in leaves and rhizomes) and Ca (in leaves, rhizomes and roots) of ponds in group B.

Statistically significant correlation coefficients of P, K (group A) and N, P, K and Ca (group B) with organic matter confirm the significant influence of OM on the accumulation properties of nutrients in *T. latifolia*. The content of P in bottom sediments significantly affected the content of N (in leaves and rhizomes), K and Mg (in leaves, rhizomes and roots) and Ca (in leaves) in group A. Potassium was significantly statistically correlated with P, K and Mg (in rhizomes and roots), Ca (in leaves) in the group A ponds, and K and Mg (in leaves) in group B. It was shown that the content of magnesium in bottom sediments was correlated with the content of Mg in leaves, rhizomes and roots (group A) and with N, P, Mg and Ca (group B). A slightly different situation was observed in the case of calcium. Ca contained in bottom sediments was significantly statistically correlated with P (rhizomes and roots) and Mg (in leaves) of group A ponds and with N and P (in leaves) and Mg and Ca (in rhizomes and roots) of group B.

A number of statistically significant correlations between the physicochemical properties of bottom sediments and the content of nutrients in the organs of *T. latifolia* confirm the findings of Potasznik et al. [47]. In the summer, due to intensive nutrient uptake from bottom sediments and their accumulation in *T. latifolia* [48], the outflow of pollutants to the catchment area is limited. The results of the conducted research indicate that *T. latifolia* may have a beneficial effect on the quality of water in small rural ponds exposed to the influx of pollutants from agricultural activity. This indicates the important role of this macrophyte for the environment, which, through diverse and strong accumulation abilities of N, P, K, Mg and Ca, mitigates the negative effects of human activity on aquatic ecosystems [13,22,49,50].

4. Conclusions

The conducted research allowed to identify two main factors (FC1: N, P, K and FC2: Mg, Ca) determining the content of nutrients in bottom sediments and in the leaves, rhizomes and roots of *T. latifolia* of small ponds in rural areas. The share of nutrients in the separated factors is related to the different solubility and bioavailability of their compounds. Analysis of BCF values showed that *T. latifolia* took nutrients from bottom sediments according to the series Ca > K > N > P > Mg, accumulating them in the greatest amounts in leaves (N, Ca) and roots (P, K, Mg). It was also found that the accumulation capacity of *T. latifolia* in rural ponds was significantly dependent on the content of organic matter and the pH of bottom sediments. These data clearly indicate that the accumulation capacity of the macrophyte is species-dependent but modified by the physicochemical properties of the bottom sediments. The obtained results confirm that *T. latifolia* growing on the edges of rural ponds, through differentiated and strong accumulation abilities in relation to N, P, K, Mg and Ca, significantly limits the outflow of nutrients to the catchment area, while contributing to the improvement of water properties in rural ponds.

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