Original Research

Polyphenolic Compounds in Lacustrine Sediments

Joanna Cieślewicz*

Department of Environmental Chemistry, University of Technology and Life Sciences in Bydgoszcz,
Bernardyńska 6, 85-029 Bydgoszcz, Poland

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Abstract

The objective of the present study was to compare the content of polyphenolic compounds in sediments of lakes with different types of catchment. Sediment samples for analysis were collected from the littoral and profundal zones of lakes with field or forest catchments. The study material was supplemented with select aquatic plant species. Basic physicochemical properties and the content of polyphenolic compounds were determined in the material applying the Folin-Ciocalteu method.

The results reveal that bottom sediments of forest lakes were distinguished by a higher content of polyphenols compared to sediments of field lakes (0.290 and 0.200$\%_{om}$). Aquatic plants were characterized by a highly diverse content of polyphenols (0.74-2.67$\%_{om}$); shining pondweed had the highest content.

Keywords: bottom sediments, polyphenolic compounds, aquatic plants

Introduction

Polyphenolic compounds (PC) are widespread in plants. Certain plants produce them in response to stress, injury, or fungal infection. These compounds are present mainly in leaves, floral tissues, stems and bark, and in lower concentrations in fruits and seeds. In general, polyphenols can be divided into four main groups: phenolic acids (which include hydroxybenzoic and hydroxycinnamic acids), stilbenes, tannins, and flavonoids [1, 2]. Flavonoids and phenolic acids are the most common active phenols isolated from vascular plants [3]. The content of polyphenols is usually determined in medicinal plants, including common juniper [4]; common kidney vetch [5]; plants used as herbs such as basil, oregano, and thyme [3]; tea [6]; and fruit drinks [7]; as well as in wine and chocolate [8, 9]. Bioactive polyphenolic compounds are also isolated from grasses that contain flavonoids (luteolin, tricin, apigenin C-glycoside), phenolic acids (ferulic, caffeic, p-hydroxy benzoic), triterpenes, saponins, and sterols [10]. Tannins are also found in green algae; they are rare in fungi, but often found in moss and lichens. Significant quantities of tannins are synthesized by coniferous (spruce and fir) [11] and deciduous trees such as linden, birch, or beech. Tannins and flavonoids are also present in aquatic plants (yellow and white water lilies) [12].

Johnson et al. [13] reported that common reed (*Phragmites australis*) may contain over 7 mg of phenols per gram of dry matter (as gallic acid equivalents). The Eurasian water milfoil produces polyphenolic compounds and hence it has an allelopathic effect on cyanobacteria and green algae [14-20]. As evidenced by the research conducted by Lee [21] and Aiken et al. [22], certain emergent plant species such as spike-rush (*Eleocharis smallii* L.), big bulrush (*Scirpus acutus* Muhlenb), and horsetail (*Equisetum fluviatile* L.) drive the wild rice (*Zizania palustris* L.) out of shallow waterbodies. Moreover, free-floating and submerged species such as white water lily (*Nymphaea odorata* Aiton), yellow water lily (*Nuphar variegatum* Engelm), bur reed (*Sparganium fluctuans* (Morong) Robinson), *Ceratophyllum* spp., and *Myriophyllum* spp. adversely affect rice. However, research conducted by Quayyum et al. [23] showed that the presence of these plants resulted in an increased content of polyphenols in lacustrine sediments. Polyphenolic compounds of lignin origin in soils or sediments are usually determined after oxidation in the presence

*e-mail: joanna@utp.edu.pl

of copper(II) oxide [24]. Taking into account the fact that lignin is synthesized by terrestrial vascular plants, the content of these compounds in bottom sediments can be regarded as a record of terrestrial matter inflow, thus they should not be confused with water-soluble phenolic compounds present in plants.

The present study aimed to determine the content of polyphenols naturally occurring in the bottom sediments of lakes with different land use development patterns in their catchment areas, as well as in select aquatic plant species.

Material and Methods

Determination of Sediment and Plant Material Properties

The research covered lakes located in two geological and structural units: the Szczecin-Łódź Basin and the Kuyavian-Pomeranian Anticlinorium. The surface of this area is built of Quaternary deposits, mostly boulder clay of glacial origin, as well as fluvioglacial and fluvial sand and gravel from the Pleistocene epoch. The thickness of Pleistocene deposits ranges from a few to ca. 150 m in the zone of the highest hills. The youngest Holocene deposits (peat, gyttja, and alluvial deposits), mainly of organic origin, are found in terrain depressions, e.g. river valleys, lake channels, and other types of depressions [25]. Table 1 presents the basic morphometric data and location of the studied lakes and Table 2 shows the occurrence of plant communities in lakes, zone directly the surrounding lakes and on lands outside this area. The material consisted of sediments collected with an Ekman sampler from the surface layer of sediments (0-20 cm) in the littoral (A) and profundal (B) zones of lakes with field (P) and forest (L) catchment areas. Air-dried samples were homogenized and sieved through a 1 mm mesh. In the prepared material, the content of total carbon (TC) and total nitrogen (TN) was determined using a Vario Max CN analyzer (Elementar, Germany), and the content of inorganic carbon was assessed using a Primacs^{sc} analyzer (Skalar, Breda, the Netherlands).

Based on the results, the content of total organic carbon (TOC) was calculated from the difference, i.e. TOC=TC-TIC. The weight content of organic matter in sediment was also determined after combustion at a temperature of 550ºC. The content of inorganic carbon was expressed as a percentage of calcium carbonate (IC·8.33), based on which type of sediment was determined [26]. The electrometric method was used to determine the water pH value (1:5 ratio, i.e. 10 g sediment:50 ml water) and a conductometric method was used to determine the specific conductivity (χ) in a paste (1:2 ratio, i.e. 10 g sediment:20 ml water). As pH is a logarithmic value, and following the recommendations of Gruba et al. [26], Table 2 presents the median value instead of the mean value.

In a similar way, the content of TC and TN was determined in aquatic plants (yellow water lily, shining and clasping-leaf pondweeds, water soldier, common reed, narrow leaf cattail, common hornwort). The weight content of

Table 1. Basic morphometric data and location of the studied lakes [28-30].

Lake	Area (ha)	Depth (m)	Length (m)	Width (m)	Shoreline length (m)	Catchment area (km^2)	Main type of soil in the catchment	Location	Water depth at the sampling site (littoral/profundal) (m)
Located in field (P)									
Pawłowskie	17.40	5.25	9.50	260	2350	63*	Cambisols, proper Phaeozems, Arenosols	Chodzież Lake District	2.0/5.2
Murwinek	3.50	0.80	350	125	900			Chodzież Lake District	0.3/0.8
Strzałkowo	26.88	8.00	970	300	2664			Chodzież Lake District	1.5/8.0
Bobrów	16.56	5.70	1120	200	2460	2.94	Cambisols, Phaeozems, Histosols	Wałcz Lake District	1.0/4.7
Located in forest (L)									
Czworokątne	7.66	5.00	530	245	1375	0.43	Cambisols	Chodzież Lake District	1.2/5.0
Sumile	10.99	3.00	705	205	1740	0.59	Cambisols	Wałcz Plain	1.5/8.0
Krępsko Małe	17.08	8.00	700	3.55	1795	172	Cambisols	Wałcz Plain	1.7/7.8
Pniewo	15.52	3.80	650	150	1940	0.86	Cambisols	Szczecinek Lake District	1.3/3.5

* 63 km^2 the catchment area of lakes Strzałkowo, Murwinek, and Pawłowskie, as well as Lakes Kaliszany, Oporzyńskie, Toniszewskie, Zbyszewickie, and Żońskie not included in research

Table 2. Plant communities occurring in the littoral zone and around the lakes [30].

Plant commmunities	Located in field (P)			
	Pawłowskie	Murwinek	Strzałkowo	Bobrów
In the littoral zone	*Ass. Nupharo-Nymphaeetum(a)* *Ass. Phragmitetum communis (rb)* *Ass. Typhetum latifoliae (rb)*	*Ass. Nupharo-Nymphaeetum (a)* *Ass. Phragmitetum communis(rb)* *Ass. Typhetum latifoliae (rb)* *Ass. Acoterum calami(rb)*	*Ass. Nupharo-Nymphaeetum (a)* *Ass. Phragmitetum communis(rb)* *Ass. Typhetum latifoliae (rb)*	*Ass. Nupharo-Nymphaeetum (a)* *Ass. Phragmitetum communis(rb)* *Ass. Typhetum latifoliae (rb)*
Within the zone immediately around the lake	*Ass. Pruno-Crataegetum (t)* *Ass. Ligustro-Prunetum (t)* *Ass. Lolio-Cynosuretum (m)* *Ass. Cirsio-Polygonetum (m)* *Ass. Filipendulo-Geranietum (m)* *Ass. Circaeo-Alnetum (fo)*	*Ass. Salici-Franguletum (t)* *Ass. Caricetum acutiformis (m)* *Ass. Epilobio-Juncetum effusi (m)* *Ass. Filipendulo-Geranietum (m)* *Ass. Trifolio-Agrimonietum (m)* *Ass. Circaeo-Alnetum (fo)*	*Ass. Salici-Franguletum (t)* *Ass. Filipendulo-Geranietum (m)* *Ass. Trifolio-Agrimonietum (m)* *Ass. Diantho- Armerirtum (m)* *Ass. Lolio-Cynosuretum (m)*	*Ass. Filipendulo-Geranietum (m)* *Ass. Epilobio-Juncetum effusi (m)* *Ass. Circaeo-Alnetum (fo)* *Ass. Tilio-Carpinetum (fo)* *Ass. Galio silvatici-Carpinetum (fo)*
Behind the zone immediately around the lake	*Ass. Galinsogo-Setarietum (fi)* *Ass. Papaveretum argemones(fi)* *Ass. Vicietum tetraspermae(fi)*	*Ass. Lolio-Cynosuretum (m)* *Ass. Junco-Molinietum (m)* *Ass. Vicietum tetraspermae (fi)* *Ass. Galinsogo-Setarietum (fi)* *Ass Paucedano-Pinetum (fo)*	*Ass. Galinsogo-Setarietum (fi)* *Ass. Vicietum tetraspermae (fi)* *Ass. Arrhenatheretum medioeuropaeum (m)*	*Ass. Vicietum tetraspermae (fi)* *Ass. Cirsio-Polygonetum (m)* *Ass. Geranio-Paucedanetum cervariae (m)*
Plant communities	Located in forest (L)			
	Czworokątne	Sumile	Krępsko Małe	Pniewo
In the littoral zone	*Ass. Nupharo-Nymphaeetum(a)* *Ass. Phragmitetum communis (rb)*	*Ass. Nupharo-Nymphaeetum (a)* *Ass. Potamogetonetum perfoliati (a)* *Ass. Phragmitetum communis(rb)* *Ass. Typhetum latifoliae (rb)*	*Ass. Nupharo-Nymphaeetum (a)* *Ass. Potamogetonetum perfoliati (a)* *Ass. Phragmitetum communis(rb)* *Ass. Scripetum lacustris (rb)* *Ass. Equisetum limosi(rb)*	*Ass. Nupharo-Nymphaeetum (a)* *Ass. Phragmitetum communis(rb)* *Ass. Scripetum lacustris (rb)*
Within the zone immediately around the lake	*Ass. Salici-Franguletum (t)* *Ass. Caricetum acutiformis (m)* *Ass. Caricetum elatae (m)* *Ass. Filipendulo-Geranietum (m)* *Ass. Circaeo-Alnetum (fo)*	*Ass. Geranio-Paucedanetum cervariae (m)* *Ass. Circaeo-Alnetum (fo)* *Ass. Ribo nigri-Alnetum (fo)* *Ass. Querco roboris-Pinetum (fo)* *Ass. Tilio-Carpinetum (fo)*	*As. Caricetum acutiformis (m)* *Ass. Circaeo-Alnetum (fo)* *Ass. Stellario-Carpinetum (fo)* *Ass. Ribo nigri-Alnetum (fo)*	*Ass Salici franguletum (t)* *Ass. Circaeo-Alnetum (fo)*
Outside the zone immediately around the lake	*Ass. Pruno-Crataegetum (t)* *Ass. Papaveretum argemones(fi)* *Ass. Galio silvatici-Carpinetum (fo)* *Ass. Potentillo albae-Quercetum (fo)* *Ass. Querco roboris-Pinetum (fo)*	*Ass. Querco roboris-Pinetum (fo)*	*Ass. Paucedano-Pinetum (fo)* *Ass. Stellario-Carpinetum (fo)* *Ass. Melico-Fagetum (fo)*	*Ass. Vicietum tetraspermae (fi)* *Ass. Potentillo albae-Quercetum (fo)* *Ass. Querco roboris-Pinetum (fo)*

(*a*) – aquatic communities, (*rb*) – communities of reed-beds, (*m*) – meadow communities, (*t*) – thicket communities, (*fi*) – field communities, (*fo*) – forest communities organic matter in plant material was determined after combustion at 550ºC.

Since there are no comprehensive reports available related to the content of polyphenols in sediments, common thyme (*Thymus vulgaris*; a commercial product of Prymat) was analyzed the same way to verify the results, which were then compared with the data presented by Modnicki and Balcerek [3].

Determination of Total Polyphenolic Content in Bottom Sediments and Plant Material

The total content of polyphenols was determined by a colorimetric method using the Folin-Ciocalteu reagent [31]. The determination is based on the reversible reduction of molybdenum(VI) to molybdenum(V) (contained in the Folin-Ciocalteu reagent) by phenols in an alkaline environment.

Extraction

A weighed amount of dry and homogenized sediments was extracted in 150 ml of distilled boiling water in a water bath for 30 min. The content of the flask was then cooled under a stream of water, quantitatively transferred to a measuring flask, and filled with distilled water to a volume of 250 ml. After sedimentation, the solution was filtered and the initial 50 ml was discarded. The reference plant material was treated in a similar way.

Measurements

Next, 5 ml of extract was diluted with distilled water to a volume of 25 ml, followed by a mixture prepared based on 1 ml of the Folin-Ciocalteu reagent, 10 ml of distilled water, and 2 ml of the diluted extract. This prepared solution was made up to a volume of 25 ml with sodium carbonate solution (290 $g \cdot dm^{-3}$). Values of absorbance were measured after 30 min of incubation in the dark at a wavelength of 760 nm. The blank determination consisted of a mixture of solutions with distilled water instead of the extract.

The total content of polyphenols was calculated according to the formula:

$$X = \frac{6.25 \cdot A_E \cdot m_P}{A_P \cdot m_E}$$

...where:

X – total content of compounds expressed as pyrogallol equivalents [%]

A_E – absorbance values of the analyzed extract

A_P – absorbance values of the pyrogallol solution

m_E – the weight of a sample [g]

m_P – the weight of pyrogallol [g]

To make the standard solution (pyrogallol), 50 mg of pyrogallol was dissolved in water using volumetric flasks with a capacity of 10 ml. 5 ml of the obtained solution was diluted to a volume of 100 ml. The absorbance of 2 ml of the pyrogallol solution, after adding the appropriate reagents, was measured in a similar way as the absorbance of solutions of the sediment samples.

Analytical Curve of Gallic Acid

8.6 mg of gallic acid was dissolved in water using volumetric flasks with a capacity of 10 ml; 1 ml of the obtained solution was diluted to a volume of 10 ml. To prepare an analytical curve, 1, 2, 3, and 4 ml of the diluted solution were again diluted to a volume of 10 ml, then 1 ml of each solution was mixed with 1 ml of the Folin-Ciocalteu reagent and 10 ml of distilled water, and made up to a volume of 25 ml with sodium carbonate solution. Measurements of the absorbance were taken at a wavelength of 760 nm after 30 min of incubation in the dark. Based on the results, a calibration curve was plotted and a curve equation was determined using Microsoft Excel.

Due to the fact that the sediments contained carbonates, the comparison of the obtained results was difficult. Therefore, the results are presented as the content of dry matter of sediment (result with dm index) and as the content of organic matter (results with om index). The analysis of variance is a commonly used statistical method allowing for the assessment of the significance of differences of many average values. Two-way analysis of variance with replication was applied for statistical analysis.

The UV spectra of the aqueous extracts of polyphenolic compounds were also analyzed [32]. Fig. 1 presents examples of the normalized spectra following the extraction of 1 g of material.

Results and Discussion

Characteristics of Bottom Sediments and Plant Material

Bottom sediments of lakes were distinguished by a highly diverse content of both organic and inorganic carbon, as well as total nitrogen. The average content of TOC was lower in the sediments of field lakes, whereas the content of inorganic carbon and total nitrogen was higher compared to sediments of forest lakes. Deposits of field lakes were also characterized by slightly higher pH values and electrical conductivity (Table 3).

Compared to sediments, the content of total carbon and total nitrogen in aquatic plants was much higher and ranged from 337.6 to 426.2 $g \cdot kg_{dm}^{-1}$, and from 22.2 to 43.0 $g \cdot kg_{dm}^{-1}$, respectively (Table 4), with the highest content in the yellow water lily. Table 5 presents a comparison of the TC and TN content in the analyzed aquatic plants reported in the literature. Values of the total carbon content obtained in this study were similar. The differences, particularly in the content of total nitrogen, may have resulted from the variability of plants, but also from the applied analytical methods. At present, CN analyzers are used in the determination of carbon and nitrogen, and the results presented in older publications come from analyses performed using the methods

Table 3. Physicochemical properties of sediments.

Lake and sampling location		TOC $g \times kg_{dm}^{-1}$	IC $g \times kg_{dm}^{-1}$	TN $g \times kg_{dm}^{-1}$	OM %	Sediment type	pH_{H_2O}	χ $\mu S \times cm^{-1}$
Located in field (P)								
Pawłowskie	A	125.5	46.5	11.1	21.8	clayey-calcareous gyttja	6.93	2290
	B	134.8	52.3	11.1	23.5	clayey-calcareous gyttja	6.93	2190
Murwinek	A	181.9	37.1	18.2	31.7	detrital-calcareous gyttja	7.15	3630
	B	190.8	30.6	18.8	33.2	detrital-calcareous gyttja	6.96	3130
Strzałkowo	A	186.4	15.2	13.6	32.4	clayey gyttja	6.94	2280
	B	199.8	25.6	15.4	33.0	detrital-calcareous gyttja	7.30	2300
Bobrów	A	112.4	0.0	8.6	19.6	clayey gyttja	6.89	1657
	B	127.6	7.1	11.2	22.2	clayey gyttja	6.98	1887
Average for A-B		157.40	26.80	13.50	27.18	–	6.95*	2420.5
Located in forest (L)								
Czworokątne	A	227.6	42.6	16.5	39.6	detrital-calcareous gyttja	6.76	2800
	B	380.0	4.3	19.0	66.1	coarse detritus gyttja	6.69	2220
Sumile	A	145.2	19.2	10.8	25.3	detrital-calcareous gyttja	6.54	1885
	B	89.9	27.7	7.4	15.6	coarse detritus gyttja	6.74	2690
Krępsko Małe	A	85.9	13.5	4.2	15.0	clayey gyttja	7.06	1431
	B	85.3	61.9	3.9	14.8	calcareous gyttja	7.45	1787
Pniewo	A	188.0	0.0	12.0	32.7	sandy-clayey gyttja	4.60	1480
	B	184.6	0.0	14.1	32.1	sandy-clayey gyttja	4.43	1712
Average for A-B		173.31	21.15	10.99	30.15	–	6.81*	2000.6

*pH values were presented as medians

Table 4. Chemical properties of aquatic plants and common thyme.

Plant	TC $g \times kg_{dm}^{-1}$	TN $g \times kg_{dm}^{-1}$	OM %
Yellow water lily (*Nuphar lutea* L.)	426.2	43.0	91.48
Water soldier (*Stratiotes aloides* L.)	337.6	38.9	66.85
Clasping-leaf pondweed (*Potamogeton perfoliatus* L.)	385.1	25.6	88.82
Shining pondweed (*Potamogeton lucens* L.)	367.9	23.2	88.18
Common hornwort (*Ceratophyllum demersum* L.)	349.8	28.0	83.94
Broadleaf cattail (*Typha latifolia* L.)	411.3	22.2	90.50
Common reed (*Phragmites australis* (Cav.)Trin. ex Steud)	416.3	27.2	90.18
Common thyme (*Thymus vulgaris* L.)	454.3	25.6	91.06

of Tiurin and Alten (carbon) and Kjeldahl (nitrogen) [33], and there are only a few more recent papers using newer techniques.

Fig. 1 presents examples of the standard spectra of polyphenols extracted from the bottom sediments and analyzed plants. The obtained spectra of phenols extracted from lacustrine sediments were characterized by nearly monotonic shapes with no clear peaks. On the other hand, one or two minor inflections were distinguished in the spectra obtained for aquatic plants at wavelengths of 267-271 nm and 320-325 nm. They were characterized by low intensity, and hence it was difficult to consider them as typical absorption maxima. Two peaks of high intensity at wavelengths of 287 and 323 nm were present only in the spectra obtained for thyme aqueous extracts.

Table 6 presents the content of phenols in the bottom sediments. No statistically significant differences were found in the phenolic content of sediments when applying the conversion to polyphenolic compounds content in dry sediment mass. As evidenced by the calculations performed based on the sediment organic matter content, there were no significant differences in the content of polyphenols between littoral and profundal sediments (A–B), but there were significant differences between the catchment types.

Table 5. The content of total organic carbon and total nitrogen according to different authors.

Plant	TC $g \times kg_{dm}^{-1}$	TN $g \times kg_{dm}^{-1}$	Source
Yellow water lily	440.0	29.2	[34, 35]
Clasping-leaf pondweed	430.0	11.5	[34, 36]
Shining pondweed	–	12.0-24.0	[36]
Common hornwort	350	34.2-34.4	[37, 38, 39]
Broadleaf cattail	460.0	–	[34]
Common reed	464.0-486.0	1.8-4.1	[34, 40]

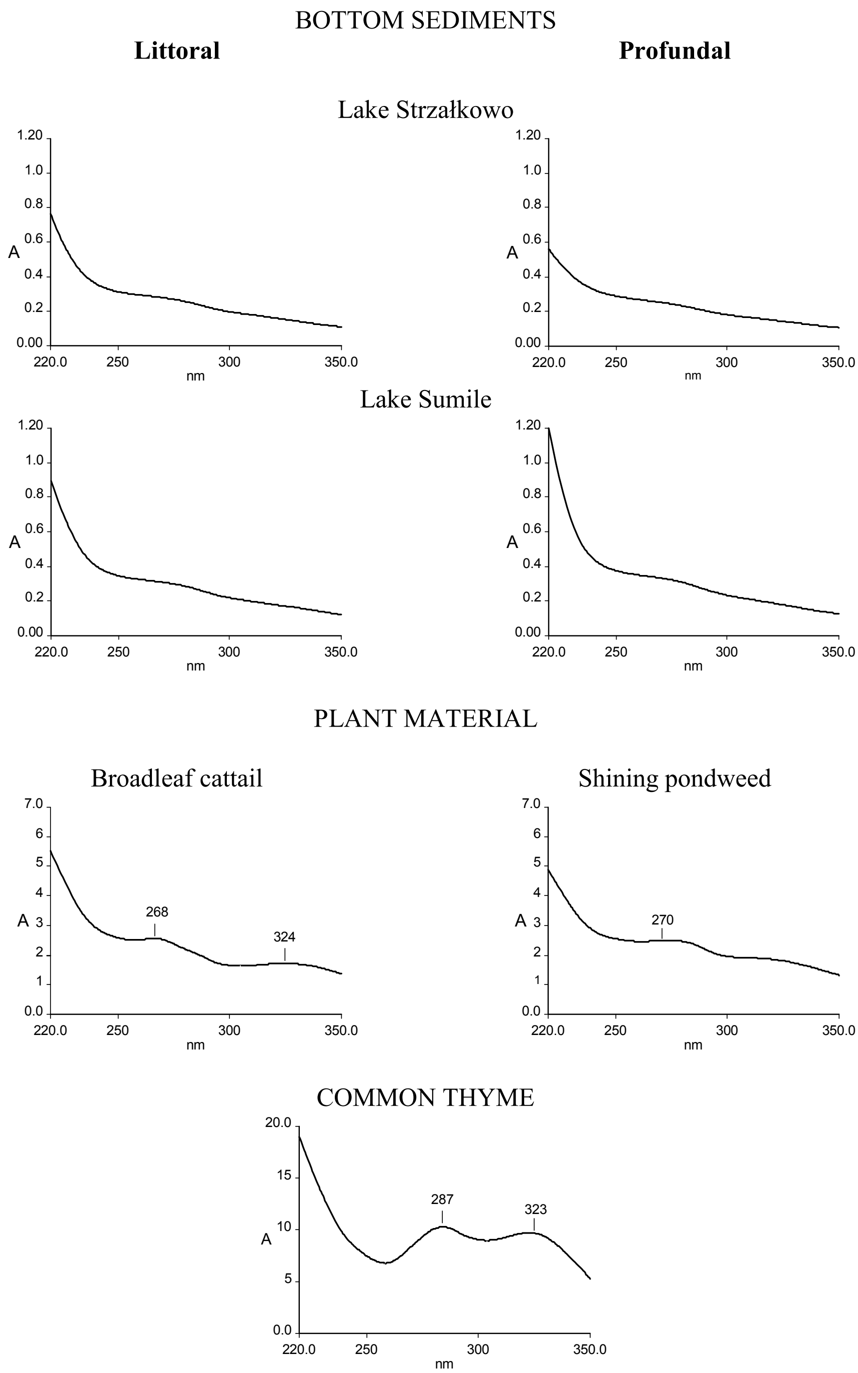

Fig. 1. Normalized spectra for 1 g extraction of dry sediment or plant material.

Table 6. The content of polyphenols in lacustrine sediments.

Bottom sediments	The content of phenols (as pyrogallol equivalents)		The content of phenols (as gallic acid equivalents)	
	$\%_{dm}$	$\%_{om}$	$mg \times g_{dm}^{-1}$	$mg \times g_{om}^{-1}$
PA	0.034–0.073	0.174–0.231	0.305–0.654	1.557–2.064
	0.051	0.191	0.457	1.710
LA	0.044–0.110	0.193–0.334	0.391–0.978	1.727–2.991
	0.074	0.263	0.657	2.403
PB	0.041–0.079	0.183–0.237	0.363–0.703	1.634–2.119
	0.060	0.209	0.534	1.870
LB	0.038–0.119	0.164–0.475	0.336–1.060	1.469–4.245
	0.084	0.312	0.749	2.790
Average value for A	0.062	0.230	0.557	2.056
Average value for B	0.072	0.260	0.641	2.330
LSD, $p < 0.05$	n.s.	n.s.	n.s.	n.s.
Average value for P	0.055	0.200	0.495	1.790
Average value for L	0.079	0.290	0.703	2.596
LSD, $p < 0.05$	n.s.	0.058	n.s.	0.518

Table 7. The content of polyphenols in plant material.

Plant	The content of phenols (as pyrogallol equivalents)		The content of phenols (as gallic acid equivalents)	
	$\%_{dm}$	$\%_{om}$	$mg \times g_{dm}^{-1}$	$mg \times g_{om}^{-1}$
Yellow water lily	1.08	1.18	9.64	10.54
Water soldier	0.57	0.86	5.11	7.64
Clasping-leaf pondweed	0.66	0.74	5.86	6.60
Shining pondweed	2.35	2.67	21.02	23.84
Common hornwort	1.00	1.19	8.93	10.64
Broadleaf cattail	0.98	1.09	8.78	9.70
Common reed	0.78	0.87	6.99	7.75
Common thyme	2.85	3.13	25.52	28.03

Based on the obtained results, it was found that sediments of forest lakes were distinguished by a higher content of PC compared to field lakes. This probably results from the heterogeneity of organic material occurring in the area surrounding the lakes. Water-soluble polyphenolic compounds may reach the aquatic ecosystems through runoff. The PC content in plants occurring in agroecosystems is usually lower compared to vegetation occurring in forest ecosystems. For example, the content of polyphenolic compounds in cereals may range from 0.2 $mg \cdot g_{dm}^{-1}$ in wheat grains (*Triticum aestivum*) to 1.0 $mg \cdot g_{dm}^{-1}$ in wheat bran. A much higher PC content was recorded in both deciduous and coniferous trees. The content of polyphenols in leaves and needles of various trees may range from 27.5 $mg \cdot g_{dm}^{-1}$ in leaves of silver willow (*Salix alba*) to 155.3 $mg \cdot g_{dm}^{-1}$ in spruce needles (*Picea abies*) [41].

There were also large differences in the content of polyphenols in aquatic plants; the values ranged from 0.57 to 2.35%dm (water soldier and shining pondweed, respectively) (Table 7). When comparing the polyphenolic compounds content in the common reed with data presented by Balcerek et al. [10], it appears that the content in the present study was similar and amounted to $0.78\%_{dm}$ and $0.81\%_{dm}$, respectively, whereas Johnson et al. [13] found that common reed (*Phragmites australis*) may contain more than 7 mg of phenols per gram of dry matter (as gallic acid equivalents).

The content values obtained by Kähkönen et al. [41] for common reed, cattail and thyme were 5.7, 8.2 and 17.1 mg of phenols per 1 g of dry matter, respectively (as gallic acid equivalents). Other studies presenting the content of polyphenolic compounds in aquatic plants are available [42, 43], although the applied conversion to tannic acid makes it difficult to compare the results. It should be noted, however, that Smolders et al. [43] also reported large differences in the content of polyphenols in the analyzed pondweed species. Clasping-leaf and shining pondweeds contained, respectively, 19 and 67 mg of polyphenols per 1 g of dry matter (as tannic acid equivalents). Similar large differences in the polyphenolic content were obtained in the presented study. On the other hand, the polyphenolic content calculated per gram of organic matter had the lowest values in shining pondweed, i.e. $0.74\%_{om}$ and $6.60\ mg \cdot g_{om}^{-1}$, and the highest in clasping-leaf pondweed, i.e. $2.67\%_{om}$ and $23.84\ mg \cdot g_{om}^{-1}$.

As evidenced by the comparison of polyphenolic content in common thyme with the literature data, the content of $2.85\%_{dm}$ calculated as pyrogallol equivalents was lower compared to the values obtained by Modnicki and Balcerek [3], and ranged from 3.37 to $3.56\%_{dm}$.

Conclusions

Compared with an herb plant, i.e. common thyme (*Thymus vulgaris* L), the content of polyphenols in aquatic plants was much lower (except for *Potamogeton lucens* L.), although considerably higher compared to the analyzed bottom sediments. Irrespective of the method used to calculate the polyphenolic content, no statistically significant differences were found in the content of polyphenols in the littoral and profundal sediments.

The bottom sediments contained inorganic carbon in the form of carbonates that come from shells and exoskeletons of aquatic animals, as well as the biological decalcification of water. The content of carbonates makes the interpretation of the results difficult. No statistically significant effect of development of the area surrounding the lakes on the content of polyphenolic compounds was found when the content was expressed as dry mass of sediment. On the other hand, after eliminating the effect of carbonates and using the content of organic matter in bottom sediments, it was found that development of the area around the lakes significantly affects the content of polyphenols, because higher concentrations were recorded in the bottom sediments of forest lakes.

It can be concluded that lacustrine sediments are characterized by a low content of polyphenolic compounds. Different use of land around the lakes is an important factor affecting polyphenol content. Further research with chromatographic techniques is required for qualitative analysis of polyphenolic compounds present in bottom sediments.

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