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SEDIMENTS, SEC 5 • SEDIMENT MANAGEMENT • RESEARCH ARTICLE

Recycling of bottom sediment to agriculture: effects on plant growth and soil properties

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Abstract

Purpose The use of bottom sediments in agriculture reduces the storage of excavated material and allows the nutrients it contains to be applied for soil fertilisation and improvement. However, the direct application of sediments to soil may cause numerous problems. Therefore, the addition of other waste materials may be a promising and useful method in the production of bottom-sediment-based growing media. The aim of the study was to evaluate the effect of growing media prepared on the basis of bottom sediments and various waste materials on the properties of soil as well as on the yield and chemical composition of courgette biomass.

Methods The growing media were prepared with substrates in the form of mixtures with bottom sediments taken from the Rożnów reservoir. The effect of mixtures on plant growth was determined in a laboratory pot experiment. Air-dry mixtures (M1—bottom sediment with water treatment sludge (BS + SW); M2—bottom sediment with biomass ash (BS + BA); M3—bottom sediment with coffee hulls (BS + CH)) were mixed with soil (S) in the following proportions: combination I—25%, combination II—50%, combination III—75%, and combination IV—100% mixture.

Results The media did not have harmful effects on the plant or the soil environment. They had deacidifying properties; high contents of calcium, magnesium, potassium, and phosphorus; low total trace element content; and posed little risk of metal mobility. *Heterocypris incongruens* was the organism most sensitive to the substances contained in the studied media. The use of bottom-sediment-based media reduced the biomass of the test plant and, at the same time, limited the accumulation of trace elements in its aboveground parts.

Conclusion Most of the analysed media were low-toxic to the test organisms and can potentially be used in agriculture, horticulture, or the reclamation of degraded land.

Keywords Use and recycle bottom sediment · Growing medium · Nutrients · Circular economy

1 Introduction

Bottom sediments are an integral part of the aquatic environment. They are the product of all processes taking place both in the aquatic environment and in the whole catchment area. Their excessive accumulation leads to reduced retention capacity, progressive shallowing of reservoirs, and, indirectly, damage of turbines at dams (Renella 2021).

Dredging of reservoirs generates a large amount of sediment that requires appropriate management or disposal (Akcil et al. 2015; Kazberuk et al. 2021; Ferrans et al. 2021). According to estimates by the European SedNet network, 200 million m^3 of sediment is excavated annually in Europe (SedNet 2004). Therefore, the direction of dredged material management should be chosen based on the analyses of the physicochemical properties

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and the degree of contamination of the sediment (Baran et al. 2016a, b; Couvidat et al. 2018; Ferrans et al. 2019). Spadaro and Rosenthal (2020) suggest using the circular economy model to reduce and reuse bottom sediment in the environment. The main applications of bottom sediments include use in construction, civil engineering (reinforcement of slopes, embankments, banks), agriculture, horticulture, landscaping, and in the reclamation of degraded areas (Canet et al. 2003; Tarnawski et al. 2015, 2017; Mattei et al. 2017; Baran et al. 2019a; Urbaniak et al. 2020a, b; Renella 2021).

Different approaches related to the classification of bottom sediment quality may be observed in various EU countries (Heise 2018). In Finland and the Czech Republic, the direct reuse of sediment dredged from water bodies onto agricultural soils is allowed if the content of contaminants is below the threshold limits of the respective national legislation (Kiani et al. 2021). In Poland, there is no legal possibility to recover the bottom sediment using the R10 method—"Land treatment resulting in a benefit to agriculture or improving the environment as well as the types of waste acceptable for such recovery" (Journal of Laws-item 130, 2015). The possibility of using bottom sediments in agriculture in Sweden is regulated by the ratio between the content of cadmium and phosphorus (Djerf and Ferrans 2022). What is noteworthy is the lack of quality criteria for bottom sediments regarding contamination with microplastics or pharmaceuticals. In addition, the integration of chemical and ecotoxicological analyses has been shown to be important in the decision-making process for the management of bottom sediments on land (Heise 2018). Renella (2021) proposed that nutrient-rich recycled sediments should be reconsidered as a component material category in the new EU regulation on fertilisers.

The application of bottom sediments in agriculture, horticulture, or the reclamation of degraded land may improve the physicochemical properties of soils/land and increase the availability of nutrients for plants (Sigua 2009; Baran et al. 2019a). The potential benefits of using bottom sediments in agriculture and horticulture depend on their physicochemical and ecotoxicological properties. Sediment characteristics such as high content of organic matter and bioavailable forms of macro- and micronutrients, neutral or alkaline pH, high silt, and clay fractions mean that sediment addition can improve the structure and sorption properties of soils, especially light and acidic soils (Canet et al. 2003; Macía et al. 2014; Tarnawski et al. 2015; Renella 2021; Kiani et al. 2021). Nowadays, use and recycling of bottom sediments in agriculture could be important because many countries are looking for alternative sources of nutrients and organic carbon. Their availability in the form of fertilisers represents a key factor in the overall question of global food security. On the other hand, high contents of potentially toxic trace elements and organic pollutants can be a barrier in the use of bottom sediments (Akcil et al. 2015; Baran et al. 2019c; Ferrans et al. 2019).

Numerous studies indicated the possibility of using bottom sediments as an addition to soils (Canet et al. 2003; Sigua 2009; Tarnawski et al. 2017; Baran et al. 2019a; Urbaniak et al. 2020a, b; Kazberuk et al. 2021; Kiani et al. 2021), which may be a good alternative for the land-based management of dredged bottom sediments. Phytoremediated sediments can be used as alternatives to traditional nursery substrates for ornamental plants (Mattei et al. 2017) and forest trees (Ugolini et al. 2018). On the other hand, Sigua (2009) highlighted the possibility of using bottom sediments for fodder crop production. That author presented the beneficial effect of adding sediments from Lake Panasoffkee (FL, USA) to the soil, which consisted in improving the structure of sandy soils, contributing to water retention and proper soil aeration.

However, the direct application of bottom sediments to soil may cause numerous ecological and technical problems (Macía et al. 2014; Szara et al. 2020a, b). Therefore, the addition of other waste materials may be innovative, promising, and useful in the production of bottom-sediment-based growing media. Macía et al. (2014) found that the composting of bottom sediments with waste rich in organic matter would result in valuable fertiliser material. Our previous studies also revealed that mixtures prepared on the basis of bottom sediments of the Rożnów reservoir and biomass ash, coffee hulls, and water treatment sludge can be a potential substrate for the production of media used in agriculture, horticulture, and the reclamation of degraded land (Szara et al. 2020b).

The aim of this study was to evaluate the effect of growing media prepared on the basis of bottom sediments collected from the Rożnów reservoir and waste materials on the chemical and ecotoxicological properties of soil as well as on the yield and chemical composition of courgette biomass.

2 Material and methods

2.1 Materials

The growing media were prepared with substrates in the form of mixtures with bottom sediments taken from the Rożnów reservoir. The Rożnów reservoir is located in the Lesser Poland Voivodeship in southern Poland (Baran et al. 2019b).

Three mixtures were prepared: M1, M2, M3, which were obtained after mixing bottom sediment and waste material in the ratio of 75 to 25% (Szara et al. 2020a, b). Mixture M1 consisted of bottom sediment (BS) and water treatment sludge (SW), mixture M2 of bottom sediment (BS) and biomass ash (BA), and mixture M3 of bottom sediment (BS) and coffee hulls (CH). To stabilise the mixtures, they were subjected to a 3-month pre-incubation under controlled conditions with 40% humidity, 22–23 °C temperature, and darkness.

Our previous studies proved that the mixtures have deacidifying properties, good sorption properties, and significant contents of total organic carbon (TOC) and macro- and microelements (Table 1) (Szara et al. 2020a, b). The low total trace element contents and the low share of exchangeable fraction (F1: M1: 61% Cd, 4% Cr, 11% Ni, 25% Zn, 0% Cu, 1% Pb; M2: 49% Cd, 5% Cr, 35% Ni, 26% Zn, 2% Cu, 2% Pb; M3: 56% Cd, 2% Cr, 5% Ni, 31% Zn, 2% Cu, 1% Pb) indicate a low risk associated with the mobility and potential bioavailability of trace elements in the studied mixtures (Szara et al. 2020a, b). The experiment used light soil with a sandy loam granulometric composition, slightly acidic reaction (pH = 6.60), and low total organic carbon content (TOC 1.13%). The metal contents (mg kg^{-1}) in the soil were as follows: Zn (52.77) > Pb (18.42) > Cr (7.80) > Ni (3.40) > Cu (35.00) > Cd (0.57).

2.2 Pot experiment

The effect of mixtures on plant growth was determined in a laboratory pot experiment. The control in the experiment was soil (S) without additions. Air-dry mixtures (M1—bottom sediment with water treatment sludge (BS + SW); M2—bottom sediment with biomass ash (BS + BA); M3—bottom sediment with coffee hulls (BS + CH)) were mixed with control soil (S) in the following proportions: combination I—25%, combination II—50%, combination III—75%, and combination IV—100% mixture (Table 2SM). The experiment was carried out in 0.5-kg pots under controlled conditions in 3 replications for each combination ($n = 39$).

Five seeds of the test plant, i.e. courgette (*Astra Polka*), were sown into each prepared medium. The experiment was conducted at 20 °C, watering the plants daily to 60% humidity and maintaining the adequate photoperiod (16/8) for 30 days. At the end of the experiment, the plants were cut and the dry mass yield of the plant aboveground parts was determined using the drying and weighing method. In addition, the media and plant material were subjected to laboratory analyses.

2.3 Chemical analyses of soil-sediment mixtures and plants

In the media, the following parameters were determined: pH in H_2O by potentiometric method, total organic carbon (TOC), and nitrogen contents using a CNS elemental analyser (Vario Max Cube). Total contents of macronutrients (Ca, Mg, K, P) and trace elements (Fe, Mn, Cd, Cr, Cu, Ni, Pb, Zn) were determined after digestion in a mixture of HNO_3 (65%) and HCl (30%) (3:1 v/v), (Suprapur MERCK) and solution in a microwave system (AntonPaar Multiwave 3000). The mobility of trace elements (Cd, Cr, Cu, Ni, Pb, Zn) contained in the media was analysed by a four-step sequential chemical extraction by the modified BCR method (BCR Information Reference Materials 2001; Szara-Bąk et al. 2021). The method allowed the determination of four metal fractions: fraction F1—exchangeable, easily soluble in an acidic medium (extracted with 0.11 M CH_3COOH, pH = 2); fraction F2—reducible, bound to Fe and Mn oxides (extracted with 0.5 M NH_2OHHCl, pH = 1.5), fraction F3—oxidable, bound to organic matter (extracted with hot 30% H_2O_2 and

Table 1 Selected chemical properties of mixtures (Szara et al. 2020a, b)

Parameter		BS	M1 (BS + SW)	M2 (BS + BA)	M3 (BS + CH)
pH		7.43 a[a]	8.26 b	7.74 a	8.16 b
CEC	mmol(+) 100 g^{-1}	9.62 a	10.3 a	15.8 a	10.3 a
TOC	g kg^{-1} d.m	14.0 a	34.2 c	24.0 b	86.5 d
Mg	g kg^{-1} d.m	3.36 a	6.54 b	7.41 b	7.24 b
Ca		116.7 a	15.5 b	17.6 b	18.1 b
P		0.28 a	0.75 b	0.48 c	0.46 c
K		1.49 a	4.14 ab	2.60 ab	6.36 b
Cd	mg kg^{-1} d.m	0.22 a	0.35 b	0.21 a	0.23 a
Cr		28.3 ab	31.1 b	33.6 b	18.4 a
Ni		24.4 a	38.1 c	34.3 ab	29.9 ab
Zn		67.5 ab	88.2 b	71.4 ab	70.8 ab
Cu		16.5 a	28.7 b	28.7 b	27.8 b
Pb		8.68 a	12.8 a	13.8 a	12.4 a

BS bottom sediment, *SW* water treatment sludge, *BA* biomass ash, *CH* coffee hulls

[a] Means followed by different letters indicate significant differences between mixtures at $\alpha \leq 0.05$ according to the *t*-Tukey test

0.5 M CH_3COONH_4, pH = 2); fraction F4—residual, bound to minerals (hot digested in a mixture of HNO_3 and $HClO_3$ (3: 2 v/v)) (Baran et al. 2019c; Szara-Bąk et al. 2021).

To determine the contents of macronutrients (Ca, Mg, K, P) and trace elements (Fe, Mn, Cd, Cr, Cu, Ni, Pb, Zn), the plant material was digested in a mixture of HNO_3 (65%) and H_2O_2 (30%) (3:1 v/v) (Suprapur MERCK) and dissolved in a microwave system (AntonPaar Multiwave 3000).

Elemental concentrations in the media and plant material were determined using an inductively coupled plasma optical emission spectrometer: Perkin Elmer ICP-OES Optima 7300 DV. In chemical analyses, each sample from the above experiment was analysed in duplicate. If the results for those replicates differed by more than ± 5%, two more analyses of that sample were carried out.

The ability of the test plant to accumulate trace elements contained in the media was determined using the bioaccumulation coefficient (BC), which is defined as the ratio of the concentration of trace elements accumulated in the plant to the concentration of these elements in the soil/substrate (Ghosh and Singh 2005; Eid and Shaltout 2016):

$$\mathrm{BC} = \mathrm{CP}/\mathrm{CS} \tag{1}$$

where CP is the concentration of trace elements in plants (mg kg^{-1}) and CS is the concentration of the same trace elements in the growing media (mg kg^{-1}).

2.4 Ecotoxicological analyses of soil-sediment mixtures

The ecotoxicity of the media was assessed at the end of the experiment using three biotests: Ostracodtoxkit F, Rapidtoxkit F, and Microtox. Ostracodtoxkit F is a “first-contact” test to determine the chronic toxicity of test samples. The test procedure involves exposing juvenile *Heterocypris incongruens* to contaminants contained in the media for 6 days. At the end of our biotest, the mortality and growth inhibition of the test organisms were determined in relation to the control sample (Ostracodtoxkit F 2001; ISO 14371 2012; Szara et al. 2020a, b).

Rapidtoxkit F and Microtox tests were carried out on previously prepared aqueous extracts in a ratio of 1:4. Rapidtoxkit F determines the inhibition of food uptake by *Thamnocephalus platyurus* larvae after 60 min of exposure to substances contained in the test sample extracts. An inhibition of food particle uptake above 30% is an indicator of the presence of undesirable compounds (Rapidtoxkit 2004). The Microtox test is based on measuring the luminescence intensity of *Aliivibrio fischeri* after a 15 min incubation with a Microtox M500 analyser. The measurement of the light produced is compared to that of a control sample (Microbics Corporation 1992).

The toxicity of the media was assessed on the basis of the percentage toxic effect (PE) and assigned the appropriate toxicity classes ($PE < 20\%$ no toxic effect; $20\% \leq PE < 50\%$ low-toxic sample; $50\% \leq PE < 100\%$ toxic sample; $PE = 100\%$ very toxic sample) (Persoone et al. 2003).

2.5 Statistical analysis

Differences between mean values were analysed using two-way ANOVA and Tukey’s test at a significance level of 0.05. All statistical analyses were performed using STATISTICA 12.0 software.

3 Results

3.1 Properties of soil-sediment mixtures

3.1.1 Chemical properties

The basic chemical properties of the media are presented in Table 2. In each of the media, there was a significant increase in the pH value compared to the control treatment. The media were alkaline, while the control soil was slightly acidic (pH = 6.56). The addition of mixtures to the soil significantly increased the content of total organic carbon. The highest TOC content was found in the medium with the mixture of bottom sediment and coffee hulls (M3), lower in treatments with the mixture of bottom sediment and biomass ash (M2), and the lowest in treatments with the mixture of bottom sediment and water treatment sludge (M1). The TOC content determined in the M3 mixture treatments was 1.9 to 5.2 times higher than in the control.

In general, as the percentage share of the sediment-waste mixture in the media increased, the total content of individual elements also increased. Nitrogen content ranged from 1.13 g kg^{-1} in the control soil (S) to 6.35 g kg^{-1} in the mixture based on bottom sediment and coffee hulls (M3) in 100% combination. As compared to the control treatment, a significant increase in nitrogen content was observed in the media prepared with the mixture of bottom sediment and coffee hulls (M3) in each of the studied combinations and in the media with the mixture of bottom sediment and water treatment sludge (M1) in the 50%, 75%, and 100% combinations of the sediment-waste mixture. The average N content in the media, irrespective of the share, formed the following series: M3 (4.19 g kg^{-1}) > M1 (1.77 g kg^{-1}) > M2 (1.38 g kg^{-1}). The C:N ratio ranged from 9 (M1 in each combination and M3 in the 50 and 100% combinations) to 15 (M2 in the 100% mixture combination). On average, the highest C/N ratio value was found in treatments with M2 (13), and the lowest in treatments with M1 (9).

Table 2 Chemical properties of the growing media

Treatment		pH	TOC	N	Ca	Mg	P	K	Mn	Fe	Cd	Cr	Cu	Ni	Pb	Zn
			g kg^{-1} d.m		g kg^{-1} d.m						mg kg^{-1} d.m					
S	Control	6.56 a[a]	11.14 a	1.13 a	1.51 a	0.56 a	0.40 a	0.94 a	0.16 a	3.65 a	0.63 cd	8.62 a	38.8 ef	3.20 a	17.6 b	49.9 a
M1 + S	25%	7.77 cd	12.6 ab	1.38 ab	7.83 b	3.19 b	0.62 cde	3.23 b	0.40 bc	8.35 b	0.62 cd	21.7 b	32.5 cde	12.8 b	17.5 ab	68.3 cd
	50%	7.80 de	14.9 c	1.61 bc	14.1 c	5.58 c	0.77 ef	5.49 c	0.57 d	11.5 c	0.57 bcd	32.6 c	27.4 bcd	20.8 c	16.8 ab	78.0 de
	75%	7.83 de	17.5 cd	1.90 cd	19.1 c	7.62 d	0.88 ef	6.86 de	0.73 e	13.8 d	0.62 cd	41.7 de	31.6 cd	28.5 de	16.7 ab	88.4 ef
	100%	7.82 de	19.0 d	2.20 d	24.6 d	9.57 e	0.99 g	8.38 fg	0.90 f	15.9 de	0.63 cd	50.3 fg	34.6 de	34.8 ef	17.6 ab	98.3 f
M2 + S	25%	7.80 de	14.1 bc	1.25 ab	7.56 b	3.47 b	0.55 bc	3.31 b	0.35 b	8.71 b	0.50 bcd	21.9 b	18.2 ab	13.6 b	16.3 ab	65.0 bcd
	50%	7.81 de	17.2 cd	1.40 ab	12.5 c	5.77 c	0.72 def	5.23 c	0.47 c	12.1 c	0.44 abc	34.3 cd	21.4 ab	22.5 c	14.9 ab	61.9 bcd
	75%	7.90 ef	19.1 d	1.37 ab	17.6 c	8.30 d	0.63 cde	7.14 ef	0.62 d	15.1 de	0.37 a	44.9 ef	27.1 bcd	30.6 e	14.2 ab	63.4 abc
	100%	7.95 f	22.8 e	1.49 abc	23.0 d	10.9 f	0.66 cde	9.23 g	0.75 e	17.0 f	0.38 ab	56.8 g	31.9 cd	38.4 f	13.7 ab	66.7 bcd
M3 + S	25%	7.65 b	21.3 e	2.21 d	7.71 b	3.29 b	0.61 cd	3.71 bc	0.33 b	8.21 b	0.51 bcd	20.4 b	14.6 a	12.6 b	15.2 ab	55.7 abc
	50%	7.66 b	31.0 f	3.50 e	12.6 c	5.55 c	0.55 bc	6.17 cde	0.47 c	11.4 c	0.42 ab	31.1 c	19.8 ab	20.1 c	13.9 ab	56.8 abc
	75%	7.70 bc	46.7 g	4.73 f	17.6 c	8.07 d	0.58 cd	9.33 g	0.60 d	13.7 d	0.38 ab	42.6 e	26.3 bc	27.5 d	13.3 ab	59.9 abc
	100%	7.68 bc	58.3 h	6.35 g	22.8 d	10.2 ef	0.60 cd	11.8 h	0.75 e	15.9 de	0.36 a	54.1 g	32.8 cde	35.3 e	12.7 a	65.0 bcd

M1 mixture of bottom sediment with water treatment sludge, *M2* mixture of bottom sediment with biomass ash, *M3* mixture of bottom sediment with coffee hulls, *S* soil (control)

[a] Means followed by different letters indicate significant differences at $\alpha \leq 0.05$ according to the *t*-Tukey test

Analysis of macronutrient contents (Ca, Mg, P, K) showed that the addition of waste mixtures to the soil significantly increased the content of these elements in the media (Table 2SM). The macronutrient contents in the media ranged from 1.51 to 24.6 g Ca, from 0.56 to 10.9 g Mg, from 0.40 to 0.99 g P, and from 0.94 to 11.8 g K kg^{-1} d.m. The highest Ca and Mg contents were determined in the media with the 100% mixture based on bottom sediment and biomass ash (M2). The highest content of K was in the mixture based on bottom sediment and biomass ash (M2), and P in the media with the 100% mixture based on bottom sediment and water treatment sludge (M1). In general, treatments with the 100% mixture share contained over 90% more Ca and K and 94% more Mg compared to treatments with soil alone. On average, the highest Ca and P contents were determined in the media with the mixture M1, K in the media with the mixture M3, and Mg in the media with the mixture M2.

The contents of trace elements ranged from 0.16 to 0.90 g Mn, from 3.65 to 17.0 g Fe, from 0.36 to 0.63 mg Cd, from 8.62 to 56.8 mg Cr, from 14.6 to 38.8 mg Cu, from 3.20 to 38.4 mg Ni, from 12.7 to 17.6 mg Pb, and from 49.9 to 98.3 Zn mg kg^{-1} d.m. In the media prepared on the basis of bottom sediments and waste materials, there was a significant increase in the contents of Mn, Fe, Cr, Ni, and Zn in comparison with the control treatment. Their highest contents were recorded in the media in the combination containing 100% of mixtures M2 (Fe, Cr, Zn), M1 (Mn), and M3 (Ni). The addition of sediment-waste mixtures to the soil reduced the Cu, Cd, and Pb contents relative to the control. Significant reductions in Cd content in the media were demonstrated in treatments with M2 and M3 (50%, 70%, and 100% doses), Pb with M3 (100%), and Cu with M1 (50%, 75%), M2 (all doses), and M3 (25%, 50%, 75%). Irrespective of the applied dose, the highest average contents of Mn, Cd, Pb, Cu, and Zn were found in treatments with the mixture M1, and Fr, Cr, and Ni in treatments with the mixture M2. Generally, the lowest contents of most of the investigated trace elements (except for Cr) were determined in the M3 mixture media.

The share of trace elements in individual fractions is presented in Fig. 1. Cadmium was mainly found in the exchangeable fraction F1, from 46 (M1, 100% mixture) to 69% (M2, 25% mixture), and the reducible fraction F2, from 19 (M1, 100% mixture) to 33% (control soil). In general in the media, an increase in the share of cadmium was observed in the most mobile fraction (F1) compared to the control soil. The highest concentrations of chromium and nickel were determined in the oxidable (F3) and residual (F4) fractions. The contents varied from 15 to 32% (F3) and from 64 to 81% (F4) for chromium and from 8 to 25% (F3) and from 61 to 77% (F4) for nickel, respectively. In the other fractions, the contents of those elements were low. Compared to the control soil, there was an increase in the share of chromium in the residual fraction (F4) in all media

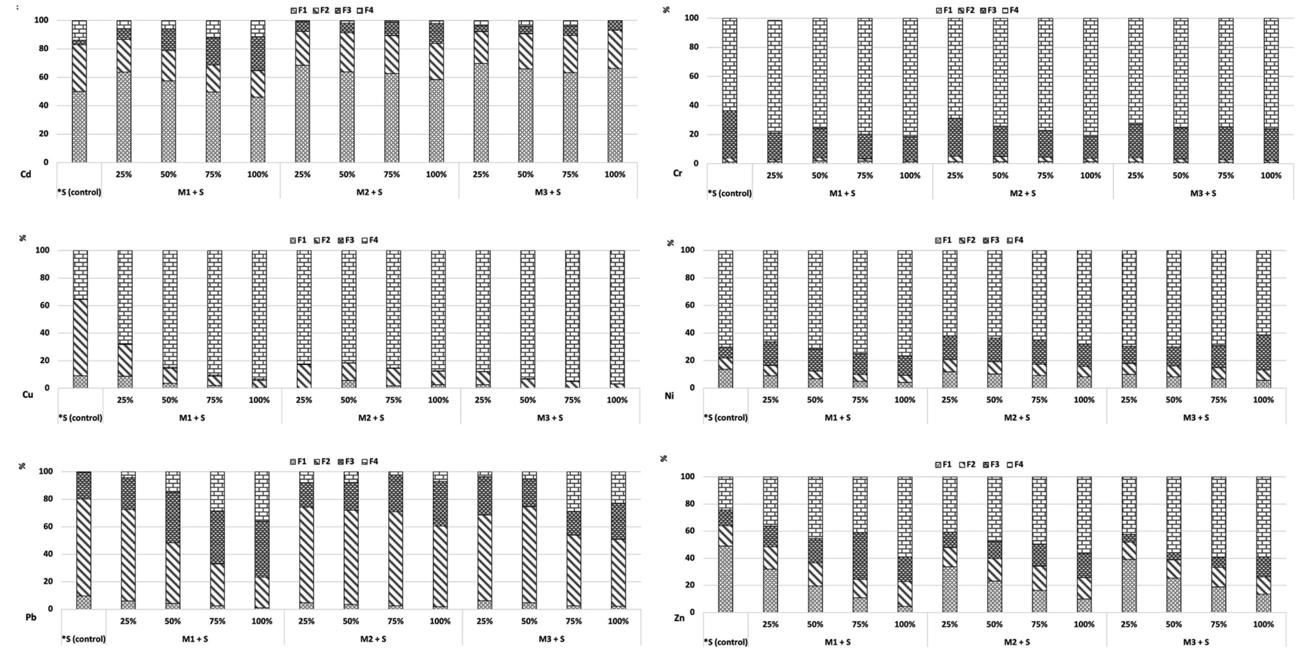

Fig. 1 Fractional distribution of trace elements in the growing media: fraction F1—exchangeable, fraction F2—reducible, fraction F3—oxidable, fraction F4—residual. *S—soil (control), M1—mixture of bottom sediment with water treatment sludge, M2—mixture of bottom sediment with biomass ash, M3—mixture of bottom sediment with coffee hulls

amended with sediment-waste mixtures, and the greatest increase was noted in the media based on bottom sediment and water treatment sludge (M1). In the control soil, the highest concentrations of copper were found in F2 (56%) and F4 (35%). The addition of sediment-waste mixtures to the soil increased the share of copper in the residual fraction (F4) in each of the studied media from 68 to 97%. Lead was present in the highest amounts in the reducible fraction F2 (from 22 (M1, 100% mixture) to 71% (S)) and the oxidable fraction F3 (from 20 (S) to 41% (M1, 100% mixture)). The most variable content in individual fractions was found for zinc. Zinc was found mainly in the exchangeable fraction (F1) and in the residual fraction (F4), and the increase in the share of waste mixtures increased the element share in the residual fraction.

3.1.2 Ecotoxicological properties

The obtained media were evaluated for their toxicity to living organisms (Fig. 2). A significant reduction in ecotoxicity of all media based on bottom sediments and waste was demonstrated for *A. fischeri* relative to the control soil. For other organisms, a reduction in ecotoxicity was shown in the treatments with M3 (all doses), M2 (100%, 50%) (*H. incongruens*), and M2 (*T. platyurus*). *H. incongruens* was the organism most sensitive to the studied media, and *A. fischeri* was the least sensitive.

In the case of bacteria, luminescence stimulation was observed in all test treatments (Fig. 2). Growth inhibition of *H. incongruens* ranged from − 4 to 59%. The highest inhibition of crustacean growth, ranging from 51 to 59%, was observed in the media based on bottom sediment and coffee hulls (M3), while the lowest in the M3 media for 100% and 50% mixture doses (PE = −3, −4). No inhibition or increased food intake (IF < 30%) by *Thamnocephalus platyurus* was found in all studied media except for those based on bottom sediment and coffee hulls (M3), in the combination of the 75% mixture (PE = 79%) and 100% mixture (PE = 81%). The studied media and the control soil were not toxic to *Aliivibrio fischeri*; in each of the investigated combinations, there was an increase in the bacterial luminescence compared to the result obtained for the control treatment (22 to 82%). The greatest luminescence stimulation occurred in the media based on bottom sediment and water treatment sludge (M1).

Most of the analysed media were non-toxic (M3, 25% combination) or low-toxic to the test organisms: media with M1 in 25% and 75% combinations, media with M2 in 25%, 50%, and 100% combinations, as well as media with M3 in a 50% combination, control soil. The other media were assigned to class III as toxic samples (M1, 50% and 100% combinations; M2, 75% combination; and M3, 75% and 100% combinations).

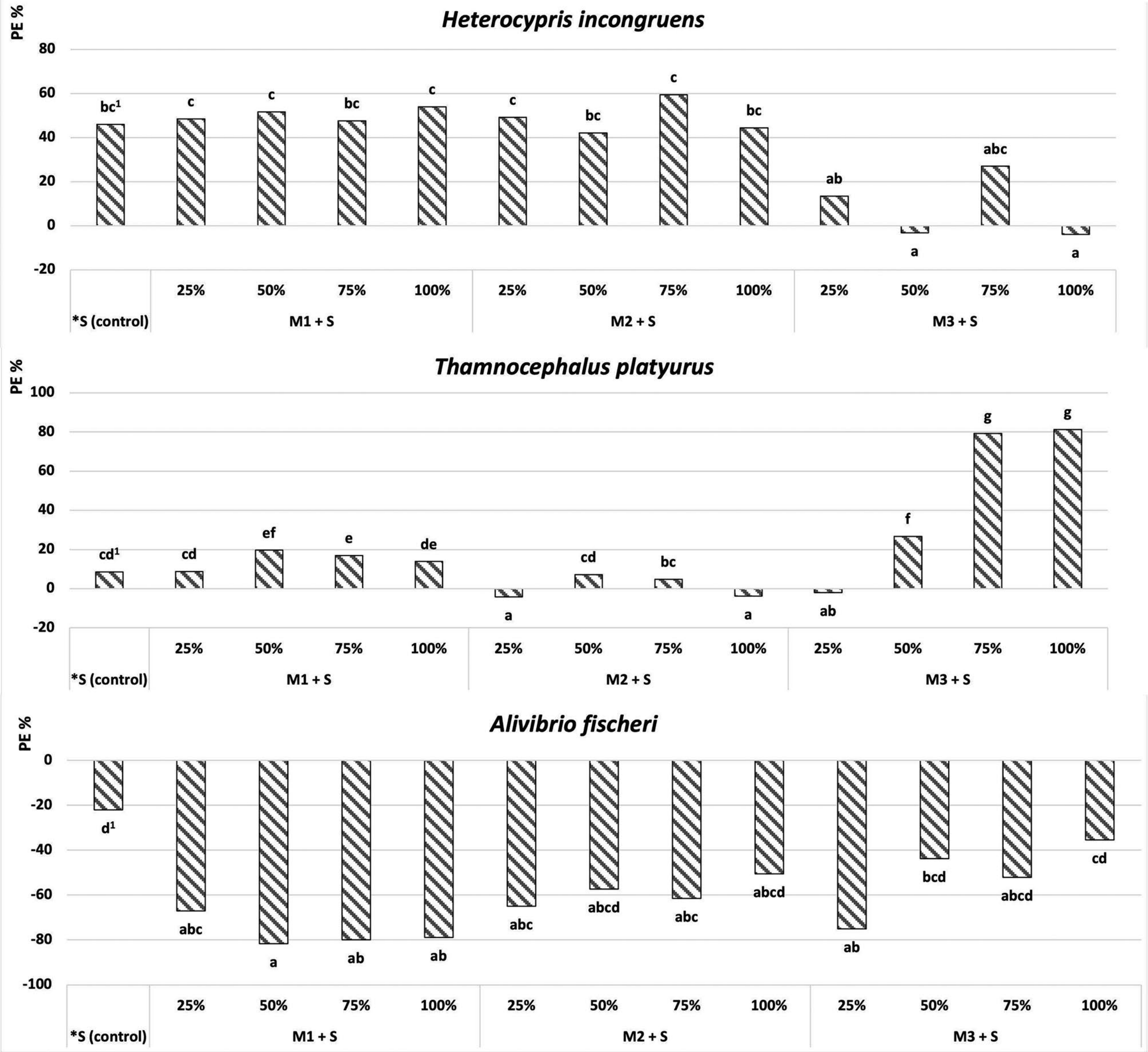

Fig. 2 Ecotoxicity of the growing media to different organisms. [1]Means followed by different letters indicate significant differences at $\alpha \le 0.05$ according to the *t*-Tukey test. *S—soil (control), M1—mixture of bottom sediment with water treatment sludge, M2—mixture of bottom sediment with biomass ash, M3—mixture of bottom sediment with coffee hulls

3.2 Plant condition

3.2.1 Biomass and chemical composition of plants

The effect of the addition of waste mixtures to the soil on the courgette biomass yield as well as the contents of macroelements and trace elements is presented in Table 3. A significant increase in the amount of courgette biomass occurred in the media with bottom sediment and biomass ash (M2) and in the media with bottom sediment and coffee hulls (M3) in the 25% combination. The application of the other media resulted in lower biomass production compared to the control.

The impact of the mixtures on the macronutrient contents in the tested plant was varied (Table 3). The contents ranged from 24.8 to 40.7 g Ca, from 6.61 to 10.4 g Mg, from 5.51 to 9.69 g P, and from 10.9 to 60.9 g K kg^{-1} d.m. Increased calcium content in the courgette biomass was found after the application of the media based on bottom sediment and water treatment sludge (M1) in 25 and 50% combinations, bottom sediment and biomass ash (M2) in 50 and 75% combinations, and based on bottom sediment and coffee hulls (M3) in a 25% combination. In the case of magnesium, the element content in the plant was increased after the use of the media based on bottom sediment and water treatment sludge (M1) and bottom sediment and biomass ash (M2) in each combination. The addition of sediment-waste mixtures to the soil significantly reduced the phosphorus content from 9.69 (S) to 5.51 g kg^{-1} (M2, 25% combination). The highest (4- and fivefold) significant increase in the potassium content in the plant was observed after the application of media with bottom sediments and coffee hulls (M3).

The contents of trace elements ranged from 0.09 to 0.19 g Mn, from 0.18 to 0.85 g Fe, from 0.05 to 0.52 mg Cd, from 2.02 to 18.3 mg Cr, from 8.39 to 17.8 mg Cu, from 1.40 to 4.12 mg Ni, from 0.63 to 1.30 mg Pb, and from 53.1 to 138.3 Zn mg kg^{-1} d.m. Additions of waste mixtures to the soil significantly increased the contents of manganese and iron, i.e. by 53% (M3, 75 and 100% combinations) and 79% (M2, 75% combination), respectively. There was a decrease in the contents of Cd, Cr, and Zn in the tested plant, which may indicate a positive effect of the waste mixtures. However, at the same time, the addition of the waste mixtures increased the copper and nickel contents. A slight increase in the lead content occurred as a result of applying the following media: M1 in 25 and 50% combinations, M2 in 25 and 50% combinations, and M3 in a 50% combination (Table 3).

3.2.2 Biomass quality indicators

Analysis of the bioaccumulation coefficient helped to determine the potential of plants to accumulate trace elements (Pachura et al. 2015; Eid and Shaltout 2016). The coefficient values ranged from 0.12 to 0.82 for Cd, from 0.05 to 1.13 for Cr, from 0.24 to 0.72 for Cu, from 0.05 to 0.49 for Ni, from 0.04 to 0.10 for Pb, and from 0.60 to 2.77 for Zn (Table 4). Plants accumulated Zn most readily (BC > 1.0) from the control treatment and from the media based on bottom sediment and coffee hulls (M3). The BC values for zinc greater than 1 were also found in treatments with the mixture of bottom sediment and water treatment sludge (M1) in combinations of 25 and 50% and in the mixture of bottom sediment and biomass ash (M2) in combinations of 50 and 75%. Moderate bioaccumulation (BC 0.1–1) occurred in each medium for Cd and Cu, in the media based on bottom sediment and water treatment sludge (M1) in combinations of 25 and 50%, bottom sediment and biomass ash (M2), and bottom sediment and coffee hulls (M3) for Cr, and in each medium in combinations of 25 and 50% for Ni. Low bioaccumulation (BC 0.01–0.1) was found in each treatment for Pb, in the media with M1 (75 and 100% combinations) for Cr, in the media with M1 (75 and 100% combinations), M2 (100% combination), and M3 (75 and 100% combinations) for Ni. The use of mixtures significantly reduced BC values for Cd, Cr, Ni, and Zn compared to the control treatment.

Table 3 Chemical composition of the test plant

Treatment		Parameter												
		Dry weight	Ca	Mg	P	K	Mn	Fe	Cd	Cr	Cu	Ni	Pb	Zn
		g pot^{-1}	g kg^{-1} d.m						mg kg^{-1} d.m					
S	Control	1.84 f	34.7 cde[a]	8.55 a	9.69 e	11.2 a	0.09 a	0.18 a	0.52 a	10.8 ab	9.39 b	1.57 ab	1.12 a	138.3 e
M1 + S	25%	1.48 d	36.1 def	9.02 b	8.29 d	14.6 b	0.11 bc	0.33 bcd	0.22 b	5.06 ab	11.7 de	1.81 bcd	1.16 abc	92.3 d
	50%	1.46 d	39.0 ef	9.19 b	8.17 d	18.1 c	0.12 c	0.29 bc	0.16 b	5.42 ab	11.4 cd	2.00 cd	1.66 c	84.1 cd
	75%	1.05 b	30.4 bc	8.92 b	7.62 cd	10.9 a	0.11 abc	0.23 ab	0.11 b	2.02 a	9.50 b	1.40 a	0.63 a	53.1 a
	100%	1.09 bc	29.9 b	8.75 b	6.86 cd	10.9 a	0.12 c	0.33 bcd	0.09 b	2.49 a	10.8 cd	1.68 ab	0.86 ab	62.1 ab
M2 + S	25%	1.90 g	31.9 bcd	10.1 c	5.51 a	10.9 a	0.09 a	0.47 efg	0.15 b	7.53 ab	8.39 a	2.09 cd	1.15 abc	60.8 a
	50%	0.89 a	40.7 f	10.0 c	7.66 cd	20.8 cd	0.11 abc	0.64 h	0.14 b	5.93 ab	13.3 f	3.63 e	1.30 bc	83.8 cd
	75%	1.63 e	36.3 efg	10.4 c	6.51 abc	22.8 d	0.12 c	0.85 i	0.16 b	9.66 abc	12.5 ef	4.12 f	1.01 ab	65.4 abc
	100%	1.12 c	35.4 ef	10.4 c	7.61 cd	22.9 d	0.11 abc	0.54 gh	0.13 b	5.48 ab	13.2 f	3.63 e	0.93 ab	62.7 ab
M3 + S	25%	1.95 g	38.7 ef	6.97 a	5.71 ab	42.4 e	0.09 a	0.42 cde	0.13 b	4.96 ab	10.6 c	1.44 a	1.04 ab	69.9 abc
	50%	1.79 f	32.5 bcd	6.61 a	6.58 abc	51.4 f	0.09 a	0.51 fg	0.06 b	18.3 c	12.7 ef	3.37 e	1.20 bc	65.2 abc
	75%	1.81 f	35.8 ef	7.37 a	5.80 ab	48.3 f	0.19 d	0.41 cde	0.05 b	9.47 abc	13.3 f	2.47 e	0.95 ab	66.5 abc
	100%	1.59 e	24.8 a	7.29 a	8.48 d	60.9 g	0.19 d	0.39 cde	0.07 b	6.38 ab	17.8 g	2.16 de	0.81 ab	82.5 bcd

M1 mixture of bottom sediment with water treatment sludge, *M2* mixture of bottom sediment with biomass ash, *M3* mixture of bottom sediment with coffee hulls, *S* soil (control)

[a] Means followed by different letters indicate significant differences at $\alpha \leq 0.05$ according to the *t*-Tukey test

4 Discussion

4.1 Influence of bottom sediment-based mixtures on soil quality

The present study results showed that the addition of bottom sediment-based mixtures had a deacidifying effect on the soil, irrespective of the mixture type and dose. The neutral or alkaline pH had media for strawberry cultivation created on the basis of bottom sediment from the Industrial Port of Livorno (Italy) and peat (Tozzi et al. 2021). Ugolini et al. (2018) found an alkaline pH of media based on phytoremediated sediments from the Navicelli Channel (Italy) used for potting holm oak (*Quercus ilex* L.). On the other hand, Urbaniak et al. (2020a, b) observed an increase in the pH value of the medium after applying to the soil 75 and 100% doses of bottom sediment from the Hudson River (USA).

The present study showed that both the dose and the type of mixtures significantly increased the total organic carbon content. The medium based on bottom sediment and coffee hulls (M3) had the highest TOC content. The C/N ratio expresses the rate of organic matter mineralisation. In the studied media, the C/N ratio ranged from 9 to 15. In the compost based on fish pond sediment and wheat straw, the C/N ratio was 12 (Dróżdż et al. 2020). The obtained media were also characterised by significant contents of potassium and phosphorus. In the study by Braga et al. (2017), the media based on bottom sediments from the Tijuquinha reservoir (Brazil) had high contents of nitrogen, phosphorus, and a significant amount of organic matter and were applied to the soil for sunflower cultivation. Kiani et al. (2021) observed that the addition of bottom sediments from the eutrophic Lake Mustijärv (Estonia) to a sandy soil increased the availability of phosphorus and other nutrients in the soil. The addition of the Rzeszów reservoir sediment in 30 and 50% doses to sandy soil significantly increased the content of available P, K, and Mg (Baran et al. 2019a). In contrast, sediments from municipal retention ponds in Gdańsk were characterised by low contents of TOC, N, P, and K, but were rich in Fe and S (Matej-Łukowicz et al. 2021).

The mixtures used also affected the trace element contents in the media. The presented results showed that the sediment-waste mixtures increased the contents of Mn, Fe, Cr, Ni, and Zn and decreased the total contents of Cu, Cd, and Pb. Similar results were obtained by Baran et al. (2019a), who demonstrated that the addition of sediment in a dose of 50% to a sandy soil increased the contents of Mn, Zn, Cu, and Ni, while decreasing the contents of Cd and Pb. Also, Kazberuk, et al. (2021), when investigating the effect of adding sediments from the Vistula and Łupia rivers and from a fish pond to a sandy soil, found elevated contents of trace elements in the media. Elevated Cd, Cr, Ni, and Cu contents in Chinese agricultural soils after the application of bottom sediments were also observed by Zhao et al. (2015).

Total trace element contents are an important indicator of soil/medium contamination; however, the information on mobility and potential toxicity to living organisms can be obtained from the presence of metals in bioavailable forms (Wieczorek et al. 2018; Baran et al. 2019c). Therefore, nowadays more attention is paid to the analysis of trace element fractionation (Nemati et al. 2011; Sungur et al. 2014). Despite the four-step sequential extraction procedure being a time and material consuming procedure, it is one of the most frequently used methods (Matong et al. 2016). Analysis of the trace element contents in individual fractions of the studied media showed that Cd occurred mainly in the exchangeable fraction. However, the risk related to the bioavailability of Cd was low given its low total content. For other trace elements, the bioavailability risk was low to medium. Additionally, the alkaline pH of the media limits the presence of elements in potentially bioavailable fractions. The important factors affecting the mobility and bioavailability of elements from soil to plants include pH, TOC, and grain size distribution (Kim et al. 2015; Baran et al. 2019a). The sediment-waste mixture has an alkaline reaction. This property might have influenced the decreased mobility of the heavy metals (Cd, Zn) from the treatments with a supplement sediment-waste mixture to plants (Table 4). In a neutral or alkaline reaction, metals occur primarily and are specifically adsorbed at hydroxyl surfaces of oxides or clay minerals (Kim et al. 2015). In the study of Baran et al. (2019a), it was found that bottom sediments added to the soil increased the content of soluble forms of Mn, Zn, Cu, and Ni and decreased the concentration of toxic metals Cd and Pb.

The applicability of growing media containing bottom sediment and other waste materials was assessed in terms of trace element contents on the basis of the criterion for soil improvers, horticultural mulch, and growing media set by the European Commission. The limits for individual metals are as follows: Cd—1 mg kg^{-1}; Cu, Cr, Pb—100 mg kg^{-1}; Ni—50 mg kg^{-1}; Zn—300 mg kg^{-1} (EU (European Union) 2015). The above limits were not exceeded in any combination of the studied media.

Estimation of the potential risk from all substances contained in the media was possible through biotests (Urbaniak et al. 2020b). Growth inhibition of *Heterocypris incongruens* was demonstrated in all studied combinations; for media based on bottom sediment and coffee hulls (M3), the inhibition was the lowest. The opposite effect was observed for that mixture in the Rapidtoxkit test. In other combinations, no effect or even an increase in food intake by *Thamnocephalus platyurus* larvae was noted. Only in the case of media based on bottom sediment and coffee hulls (M3) in 75 and 100% doses was the inhibition high, reaching 80%. In

Table 4 Trace element bioaccumulation coefficient (BC) for the tested plant

Combination		Bioaccumulation coefficient					
		Cd	Cr	Cu	Ni	Pb	Zn
S	Control	0.82 h	1.13 h	0.24 a	0.49 g	0.06 ab	2.77 g
M1 + S	25% + 75%	0.35 f	0.23 e	0.36 abc	0.14 d	0.06 ab	1.35 f
	50% + 50%	0.29 d	0.17 c	0.42 bcd	0.10 bc	0.10 d	1.08 c
	75% + 25%	0.17 b	0.05 a	0.30 ab	0.05 a	0.04 a	0.60 a
	100%	0.14 ab	0.05 a	0.31 ab	0.05 a	0.05 a	0.63 a
	Mean	0.24	0.12	0.35	0.08	0.06	0.92
M2 + S	25% + 75%	0.30 de	0.34 f	0.46 bcd	0.15 e	0.07 bc	0.94 b
	50% + 50%	0.32 def	0.17 c	0.63 de	0.16 ef	0.09 cd	1.35 f
	75% + 25%	0.44 g	0.21 de	0.46 bcd	0.13 d	0.07 bc	1.03 c
	100%	0.33 def	0.10 b	0.41 bc	0.09 b	0.07 bc	0.94 b
	Mean	0.34	0.21	0.49	0.14	0.07	1.07
M3 + S	25% + 75%	0.26 c	0.24 e	0.72 e	0.11 c	0.07 bc	1.26 e
	50% + 50%	0.14 ab	0.59 g	0.64 de	0.17 f	0.09 cd	1.15 d
	75% + 25%	0.12 a	0.22 e	0.50 cde	0.09 b	0.07 bc	1.11 c
	100%	0.18 b	0.12 b	0.54 cde	0.06 a	0.06 ab	1.27 e
	Mean	0.17	0.29	0.60	0.11	0.07	1.20

M1 mixture of bottom sediment with water treatment sludge, *M2* mixture of bottom sediment with biomass ash, *M3* mixture of bottom sediment with coffee hulls, *S* soil (control)

contrast, the Microtox test showed stimulation of *Aliivibrio fischeri* luminescence for each studied medium. Mattei et al. (2017) showed that the media based on bottom sediments from the Navicelli Channel (Italy) and green waste did not inhibit bacterial luminescence. Differences in the test organism responses may be due to both trophic group membership and the biotest procedure itself. Ostracodtoxkit F was conducted on the medium solid phase, while Rapidtoxkit and Microtox on a previously prepared aqueous extract. On the basis of the conducted biotests, it was found that the media based on bottom sediment and water treatment sludge (M1) in a 25% dose and based on bottom sediment and coffee hulls (M3) in 25 and 50% doses had low toxicity.

4.2 Influence of bottom sediment-based mixtures on plant quality

Overall, the applied media reduced the courgette biomass production. Only the application of media based on bottom sediment and biomass ash (M2) and bottom sediment and coffee hulls (M3) in a 25% dose slightly increased that parameter. Studies by Jasiewicz et al. (2011) and Baran et al. (2012, 2013, 2016a, b) assessing the suitability of bottom sediments of Besko, Zesławice, and Narożniki reservoirs for agricultural purposes revealed a positive effect of the above sediments on the maize biomass production and its chemical composition, with the highest maize yield obtained in the treatment with the lowest bottom sediment dose of 5%. The study by Niemiec (2010) also showed that a 10% dose of the Rożnów reservoir sediment was the most optimal. Higher doses of bottom sediments decreased the yield, which was caused by unfavourable air conditions in the resulting medium.

Those authors found that aboveground biomass in treatments amended with bottom sediments from the Besko and the Zesławice reservoirs was deficient in nitrogen, potassium, and phosphorus and had optimal magnesium and calcium contents (Baran et al. 2012, 2013). In our study, the courgette showed a significant increase in K, Mn, and Fe contents and a significant decrease in the P content. For trace elements, we observed a decrease in Cd, Cr, and Zn contents in the plant. In contrast, the contents of copper and nickel increased. Kazberuk et al. (2021) found that the contents of trace elements in the plant varied depending on the type and dose of bottom sediment. In general, the application of bottom sediment increased the concentrations of Cd, Zn, and Pb in plant biomass and did not affect the copper content. Tarnawski et al. (2015) showed that the addition of bottom sediment to light soil increased the copper, nickel, chromium, and lead contents in maize biomass.

The trace element contents in forage plants (Kabata-Pendias et al. 1993) was the criterion used to assess the quality of the test plant biomass. The limits for individual metals are as follows: Cd < 0.5 mg kg^{-1}; Cr < 20 mg kg^{-1}; Cu < 30 mg kg^{-1}; Ni < 50 mg kg^{-1}; Pb < 10 mg kg^{-1}; Zn < 100 mg kg^{-1}. The contents of trace elements in the biomass of the test plant grown on each of the studied media did not exceed the above limits.

In addition, the media based on bottom sediments and waste materials decreased the accumulation of Cd, Cr, Ni, and Zn in plant biomass compared to the control, as shown by the calculated bioaccumulation coefficient. Bioaccumulation coefficient values are important in determining the applicability of bottom sediments on land, in the reclamation of soils chemically degraded by heavy metals, where there is a concern about the migration of heavy metals to the above-ground parts of the plant, which, in turn, may hinder the management of such plants. In a study by Jasiewicz et al. (2010), bioaccumulation coefficient values showed that the addition of 5% of bottom sediment to the soil reduced the accumulation of Zn, Cu, Cd, Cr, and Ni in the above-ground maize biomass. The reduced coefficients of metal bioaccumulation in the test plant can be explained by the fact that the addition of bottom sediment to the soil had an alkalising effect on the soil environment and thus reduced the availability of metals to plants.

4.3 A critical look at the use of bottom sediments of the Rożnów reservoir in agriculture

It is worth noting here that attempts to use bottom sediments of the Rożnów reservoir for agricultural purposes were the subject of studies conducted by Wiśniowska-Kielian and Niemiec (2007a, b) and Niemiec and Wiśniowska-Kielian (2010). The cited studies revealed that bottom sediment dredged from the Rożnów reservoir, due to its beneficial effect of improving soil properties, can be used as an addition to acid and light soils for agricultural purposes. It was also shown that the sediment can be recommended for the reclamation of contaminated soils, given its alkaline pH favouring immobilisation of potentially toxic trace elements (Szara et al. 2020a, b). However, the aforementioned studies proved that the application of bottom sediment may cause nutrient deficiencies, particularly phosphorus deficiencies in plants in treatments with the Rożnów reservoir bottom sediments (Niemiec and Wiśniowska-Kielian 2010).

In our study, mixtures were prepared based on bottom sediments of the Rożnów reservoir and various waste materials. The study was aimed at assessing the usability of the mixtures as growing media. According to Matej-Łukowicz et al. (2021), bottom sediments from storage reservoirs are not properly balanced fertiliser products, as they have low contents of nitrogen, phosphorus, and organic carbon. However, when enriched with appropriate macronutrients and given their significant iron and sulphur contents, they can potentially be used in agriculture. Nutrient deficiencies associated with the use of bottom sediments can be mitigated by creating mixtures with materials containing significant contents of organic carbon and macronutrients. The main advantages of the mixtures prepared in this study were their deacidifying effect and significant increase in TOC, calcium, magnesium, potassium, and phosphorus contents in the media after their application. The mixtures also increased the contents of trace elements, which are valuable micronutrients (Mn, Fe, Zn). However, the use of bottom sediment-based mixtures carries the risk of introducing significant amounts of trace elements into the soil.

Nevertheless, the present study showed that metals were mainly present in potentially inaccessible fractions. The risk is also minimised by the alkaline pH of the media. In addition, the use of biotests made it possible to identify mixtures and doses not toxic to organisms. The application of the tested media inhibited the production of the test plant biomass, but the K, Mn, and Fe contents of the plants were significantly increased. The positive aspect of applying the media was also the reduced accumulation of trace elements in plants (Cd, Cr, Ni, Zn), which may result from the lower availability of metals to plants in the alkaline environment of the media.

5 Conclusions

1. Analysis of the application of mixtures based on bottom sediments from the Rożnów reservoir and waste materials revealed no harmful effects on the plant and the soil environment. This was due to the relatively low total contents of heavy metals in sediments and their low bioavailability. Moreover, the mixtures were characterised by a neutral or alkaline pH; therefore, they can be used as an addition to light and acidic soils to improve their properties. The addition of the mixtures increased the contents of TOC, K, P, Ca, Mg, Mn, Fe, and Zn in the media.
2. The conducted biotests showed that *Heterocypris incongruens* was the organism most sensitive to the substances contained in the studied media. In the case of bacteria, luminescence stimulation was demonstrated in all test treatments. Media based on bottom sediment and water treatment sludge in 25% and 75% doses, based on bottom sediments and coffee hulls in 25 and 50% doses, and based on bottom sediment and biomass ash in 25%, 50%, and 100% doses were low-toxic and can potentially be used in agriculture, horticulture, or the reclamation of degraded land.
3. The use of waste media reduced the test plant biomass while limiting the accumulation of trace elements. The application of bottom sediments helps both to avoid the storage of excavated material and to recover nutrients essential for plants.

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Availability of data and material Additional data is available on request.

Declarations

Ethical approval Compliance with ethical standards.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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