Estimation of phosphorus bioavailability from composted organic wastes

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ABSTRACT
Sewage sludge derived from municipal sewage treatment plants is an important source of macronutrients, micronutrients and organic matter. For this reason composting of sewage sludge, along with combustion and co-combustion, is a new management priority in Poland. In this study six composts of different origin and composition were evaluated in terms of their abundance in phosphorus, because it is an essential nutrient for all living organisms. Analyses were conducted on the samples at the initial and at the maturation phase of composting. The bioavailability of phosphorus was estimated on the basis of amounts of the nutrient in isolated fractions using the sequential extraction method. First of all quantitative changes of the total nutrient content and its amounts in separated fractions were dependent on the mixture composition. Irrespective of compost type, 34.5–75.0% of the total amounts of phosphorus were found in hardly available combinations (Fr. III), while available phosphorus forms (Fr. I) accounted for only 6.6–21.6%. As a result of composting together different organic wastes an increase was observed both in the total content and the amounts of this nutrient in separated fractions. This phenomenon was observed particularly in composts with smaller levels of sewage sludge (30–40%), characterised by rapid organic matter decomposition, which was indicated by higher bioavailable amounts of phosphorus. Under such conditions the content of P ranged between 3.68 and 7.4 g kg⁻¹. In comparison to the labile pool of P obtained for matured composts C5 and C6 (65 and 75% of sewage sludge in their composition) amounting to 2.45–3.0 g kg⁻¹ the above values were considerable. Bioavailable phosphorus contents potentially introduced to soil with composts doses calculated at 170 kg total N/ha/yr ranged from 69.8 to 80.2 kg for compost with the lowest share of sewage sludge and from 11.2 to 20.7 kg for compost with the highest share of sewage sludge.

Introduction
Phosphorus, together with nitrogen, potassium, sulphur and magnesium, is one of the macronutrients needed by all plants, so inputs of phosphorus are necessary to maintain profitable crop production. In order to attain this goal P should be applied between 18 and 52 kg/ha/yr. The main input of P in agriculture comes from fertilisers, but also from manures and other organic enrichments. Currently, the majority of P nutrient is applied as inorganic fertiliser derived from minerals such as phosphate rock.[1] Literature data [2,3] suggest that current high-grade reserves of phosphorus rock will be depleted within 50–150 years. Beside the quantitative aspect of resources depletion there is a qualitative problem concerned with a decreasing content of P₂O₅ and an increasing contamination with cadmium and uranium. In addition, phosphorus availability to plants is controlled by several factors connected with soil properties such as soil reaction, sorption, precipitation with Fe, Al and Ca.[4,5] According to Malik et al. [4], about 80–90% of added inorganic P becomes unavailable to plants due to unfavourable soil conditions. Therefore, a combined application of mineral and organic fertilisers is a good solution. A considerable body of literature [1,5,6] supports the view that organic matter from compost or biowastes is a very important and valuable source of P. Application of such organic substances may increase P solubility and decrease its precipitation. Moreover, organic matter incorporates significant microbial biomass, which improves phosphorus availability in the soil-plant system. Some positive mechanism might be involved such as improvement of soil pH, and complexation of soluble Al and Fe by organic molecules.[5]

Taking into account the above-mentioned factors, composts prepared on the basis of different organic wastes are an interesting soil enrichment alternative as a phosphorus source. Sewage sludge from municipal sewage sludge treatment plants ranks high among different organic wastes. In Poland in 2014 the total amount of sewage sludge generated from municipal sewage treatment plants ranged 556 thousand tonnes of dry
According to Jakubus [8], the mean content of P in sewage sludge originating from municipal sewage sludge treatment plants in the Wielkopolska region in western Poland is estimated at 23.34 g kg⁻¹, ranging from 4.9 to 67.5 g kg⁻¹. In view of the above, about 12,119 Mg of phosphorus may be incorporated and at the same time it is equivalent to 60,590 Mg of triple superphosphate. Thus, sewage sludge should be considered as an attractive waste abundant in P as well as other nutrients and organic matter, and composting of sewage sludge together with other biodegradable wastes also ensures beneficial circulation of organic matter and nutrients in the environment. Most studies concerning composts focus only on the total content of phosphorus without consideration of its availability to plants. Much greater practical importance should be attributed to the identification of chemical forms of elements in composts, and facilitating an assessment of the degree of their solubility, and thus their bioavailability. Sequential extraction methods are frequently used to evaluate various forms of elements.

A review of literature presented by Prasad [9] shows that there are few studies concerning the application of sequence extraction to assess P bioavailability from composts and these were mainly published in the early 2000s. Whilst the vast majority of studies concern the analysis of composts produced from municipal waste, green waste or manure, there are not studies detailing the current state of knowledge referring to the groups of composts produced from sewage sludge together with the various composting methods. It is known that the different types of organic wastes composted and the methods of composting may directly affect the P availability to plants. However, it is not clear what may be the direction of quantitative changes in this P component with the application of the various techniques relating to the different composting conditions and different compositions of the composted mixtures. Analysis of this aspect of research is practical and important from the point of environmental protection and rational cultivation in sustainable agriculture. Appropriate assessment of the amounts of bioavailable P released from the composts applied to the soil makes it possible to reliably determine the doses of such fertiliser so that both plant nutrient requirements can be effectively satisfied and the negative phenomena of excessive P accumulation or leaching may be avoided. In view of the above studies were undertaken aiming at the assessment of phosphorus bioavailability from composts. Quantitative variability of P in the sequentially separated fractions was analysed depending on the applied composting technique as well as the varying compost composition. The chemical characterisation of bioavailability degree of nutrient involved sequential analysis. Also phosphorus addition rate to soil with composts doses was estimated.

**Material and methods**

**Composting process, materials and sampling**

Six composts of different origin and composition were investigated. The samples were collected at the initial phase of composting (non-decomposed material) and at the final maturation phase. Experimental composts were prepared from sewage sludge supplied by mechanical-chemical sewage treatment plants located at the towns of Szamotuły (52°36'N, 16°34'E), Czarnków (52°54'N, 16°34'E) and Rumianek (52°28'N, 16°40'E) in the Poznań province, as well as wheat straw, sawdust, hemp waste, pine bark and wood cuttings. Selected properties of the components and their proportions in the composting mixture are shown in Tables 1 and 2, respectively.

| Component | Contribution (%) |
|-----------|------------------|
| Sewage sludge from Szamotuły | 45 |
| Sawdust | 50 |
| Wheat straw | 5 |
| Drawn from sewage sludge from Szamotuły | 5 |
| Sawdust | 20 |
| Wheat straw | 5 |

**Table 1. Chosen properties of composted wastes.**

| Wastes | Dry matter (%) | OM (g kg⁻¹ d m) | TOC (g kg⁻¹ d m) | Ntot (g kg⁻¹ d m) | Ptot (g kg⁻¹ d m) | C:N | C:P |
|--------|----------------|----------------|-----------------|-----------------|-----------------|-----|-----|
| Sewage sludge from Czarnków | 16.8 | 670.42 | 341 | 59.3 | 27.5 | 6:1 | 12:1 |
| Sewage sludge from Szamotuły | 16.7 | 715.65 | 330 | 53.0 | 26.7 | 6:1 | 12:1 |
| Hemp waste | 77.2 | 823.02 | 416 | 10.0 | 7.35 | 42:1 | 57:1 |
| Wood cuttings | 56.7 | 841.17 | 456 | 9.0 | 0.55 | 51:1 | 829:1 |
| Sawdust | 82.0 | 912.33 | 500 | 1.0 | 0.15 | 500:1 | 3333:1 |
| Wheat straw | 86.0 | 861.29 | 440 | 3.0 | 1.35 | 147:1 | 326:1 |

**Table 2. Composition of investigated mixtures.**

| Component | Contribution (%) |
|-----------|------------------|
| Sewage sludge from Szamotuły | 52°36'N, 16°34'E |
| Sawdust | 52°54'N, 16°34'E |
| Wheat straw | 52°28'N, 16°40'E |
| Rumianek | 52°28'N, 16°40'E |
volume of 125 dm$^3$ per chamber. The schematic diagram of the bioreactor together with its description can be found in a paper by Olszewski et al. [10]. Each composting mixture was prepared in two replications, i.e. each replication of a composting mixture was prepared in a separate bioreactor chamber. All organic wastes were well mixed prior to being transferred to bioreactor chambers. The moisture content of mixtures was 60% and the amount of air flowing through the mixtures corresponded to the volume of 4 dm$^3$/min. Each compost mixture remained in its bioreactor chamber for a period of 28 days. After that time each chamber was emptied and the contents placed in a closed room to allow maturation lasting 3 months.

Composts Nos. 1, 2, 3 and 4 were prepared as a static, trapezoidal pile. Compost piles were prepared using a specialised compost mixing machine. Each pile was prepared in two replications. The piles were mixed weekly for the first month to ensure good aeration conditions, and then at monthly intervals. Moisture content in the piles was adjusted by adding the necessary amount of water to obtain values of 60–70% of dry matter.

The procedure of material sampling was identical regardless of the composting phase. Samples were collected at five random locations in each pile and chamber. These five samples were mixed to prepare the bulk sample for each compost replication. The samples of composts were divided into fresh and dry samples, with the latter being dried at 105 °C for 12 h. The dried samples were ground into a fine powder and stored in plastic bags at a temperature of 4 °C.

### Determination of P fraction in compost

Compost samples were subjected to sequential P fractionation using a modified version of the Hedley et al. [11] procedure as described by Ajiboye et al. [12] for organic amendments. Extraction was performed sequentially using deionised water, 0.5 mol dm$^{-3}$ NaHCO$_3$ (pH 8.2), 0.1 mol dm$^{-3}$ NaOH and 1 mol dm$^{-3}$ HCl (Table 3). Samples of 0.3 g (on an oven-dry basis) of analysed composts were weighed into 30 ml of extractant inside 50 ml centrifuge tubes and shaken for 5 h at room temperature, then the samples were left overnight and on the next day they were shaken for 3 h at room temperature. The suspensions were centrifuged for 10 min at 8000 rpm and filtered. A portion of NaHCO$_3$ and NaOH extracts was acidified to precipitate the extracted organic matter and the supernatant was analysed for inorganic P. The P concentration in all extracts was determined colorimetrically using the molybdate-blue method [13] on a spectrophotometer at a wavelength of 750 nm. Total P of separated fractions was not assessed. The residual phosphorus in composts was calculated by subtracting the sum of all the P fractions from the total content in the composts.

Total P contents of composts and composted wastes were determined colorimetrically using the molybdate-blue method [13] after 1 g of samples was incinerated at 550 °C for 3 h. Then 5 ml of concentrated HCl were added to the ash and the mixture was heated for 30 min at 180 °C.

The germination index (GI) was tested using seeds of cress (Lepidium sativum L.). Compost extracts were obtained by shaking 10 g fresh matter of compost with 100 cm$^3$ distilled water for 2 h at room temperature. Ten seeds of cress were placed in Petri dishes (diameter 10 cm and depth 1.5 cm) filled with filter paper soaked up with 5 cm$^3$ compost extract and incubated in the dark for 48 h at 25 °C. The seed germination percentage and root elongation of the plants in 5 cm$^3$ distilled water were also measured and used as the control. Three replications were set out for each treatment. The percentages of relative seed germination, relative root growth and GI were calculated according to the formula presented by Miaomiao et al. [14].

### Statistical analysis

Analyses of bulk samples were carried out in three replications. The obtained results were subjected to formal evaluation with the assistance of the analysis of variance using the F test at the significance level $p \leq 0.95$. The least significant differences were calculated using the Tukey method at the significance level $\alpha \leq 0.05$ and then uniform groups within the factor level were established. Simple correlation coefficients ($r$) and determination coefficients ($R^2 \cdot 100\%$) were computed to show the relationship between total phosphorus content and the contents of the element in separated fractions of composts as well as interdependencies between GIs and amounts of phosphorus in the labile pool.

### Results and discussion

#### Total phosphorus

A number of microbiological and chemical processes take place in the course of composting, which can result amongst other things, in a loss of organic matter,
which is not confirmed in practice. However, the total content of an element does not provide information on its potential mobility in the environment.[16] A much greater practical importance is attributed to the identification of chemical forms of nutrients in composts, allowing an assessment of the degree of their solubility, and thus their bioavailability. Bioavailability for plants is connected with its solubility and decreases in the following order: water-soluble forms > adsorbed on Mn and Fe oxides > organic forms > residual forms. In relation to the above, applying methods of sequential extraction enables the degree of bioavailability for a given nutrient may be assessed more reliably. In the sequential method applied in this study fractions I and II can be ascribed to phosphorus combinations readily released in the environment, i.e. potentially bioavailable. In turn, fractions III, IV and V indicate the amounts of the element strongly bound with organic matter and the mineral portion of the analysed matrix, and thus hardly available for plants.

The distribution of P in separated fractions was slightly differentiated by the composting phase and mixture composition. Regardless of the above, a common tendency was observed for some composts. P contents in isolated fractions increased during the composting process and as a result for mature composts they amounted from 10.74 g kg⁻¹ (C1) to 19.20 g kg⁻¹ (C2) of total phosphorus (Table 4). The observed differences in the total content of this element resulted from its amounts in organic wastes used in composting (Table 1). The greatest quantitative difference between the composting phase, amounting to 42%, was observed for compost No. 1, which had the lowest total content of phosphorus. A minor quantitative difference between the composting phase, amounting to 6%, was observed for compost No. 6, which had the highest total content of phosphorus. The data presented in Figure 1 confirm the role of used wastes and their share in the composting mixture. The highest value of P (18.20 g kg⁻¹) was found in C6 and this value was 2.0 times higher than in C1, where the lowest value of P (9.15 g kg⁻¹) was recorded.

**Phosphorus in isolated fractions of composts**

When using the total amounts it is assumed that all forms of elements have an identical environmental impact, simultaneously causing a quantitative changes in nutrient levels. According to Zorpas et al. [15] the composting process can either dilute or concentrate quantities of metals, as a consequence of leaching from the decomposed organic matter or losses of the composted biomass. The results presented show that the interaction of composting time and mixture composition had a significant influence on the total P content. Regardless of compost composition and applied composting process, higher amounts of this element were recorded in matured composts (Table 4). This phenomenon was confirmed by Galvez-Sola et al. [6]. The initial P level for composting mixtures ranged from 7.56 g kg⁻¹ (C1) to 17.73 g kg⁻¹ (C6). Depending on the compost these values increased during the composting process and as a result for mature composts they amounted from 10.74 g kg⁻¹ (C1) to 19.20 g kg⁻¹ (C2) of total phosphorus (Table 4). The observed differences in the total content of this element resulted from its amounts in organic wastes used in composting (Table 1). The greatest quantitative difference between the composting phase, amounting to 42%, was observed for compost No. 1, which had the lowest total content of phosphorus. A minor quantitative difference between the composting phase, amounting to 6%, was observed for compost No. 6, which had the highest total content of phosphorus. The data presented in Figure 1 confirm the role of used wastes and their share in the composting mixture. The highest value of P (18.20 g kg⁻¹) was found in C6 and this value was 2.0 times higher than in C1, where the lowest value of P (9.15 g kg⁻¹) was recorded.

**Table 4.** Quantitative changes of total phosphorus content in composts in dependence on composting phase (g kg⁻¹).

| Composting phase | 1   | 2   | 3   | 4   | 5   | 6   |
|------------------|-----|-----|-----|-----|-----|-----|
| Initial          | 7.56| 15.62| 15.83| 11.09| 15.33| 17.73|
| Maturation       | 10.74| 19.20| 17.93| 12.72| 16.66| 18.83|
| LSD              | 0.764|     |     |     |     |     |

**Figure 1.** Total content of phosphorus in analysed composts (mean values for composting time).
was found particularly in the case of C6 for the labile P pools obtained with water and bicarbonate. It was confirmed by the non-significant correlation coefficients (Table 6). In comparison to samples collected at the initial phase, matured composts Nos. 3, 5 and 6 were characterised by a lower P content in fractions I and II and higher in fractions III, IV and V, respectively. This is in agreement with the results of Ergrinya-Eneji et al. [23] and O’Connor et al. [24]. Such a direction of P changes may suggest that the more stable composts had lower extractable P amounts than unstable compost. Content of P in fractions I, II, III and IV increased during composting of mixtures for composts Nos. 1 and 2. At this same time, as a result of composting, residual phosphorus (Fr. V) decreased by 14% (C1) and 64% (C2) (Table 5). For matured compost No.4 a higher amount of P was found in fractions I (by 16%), IV and V (2.0-fold), while a lower content of the element was recorded in fraction II (by 18%) (Table 5).

On the basis of the results it should be emphasised that compositions of composts No. 1 and 2 (Table 1) were advantageous and promoted a rapid and easy decomposition of labile organic compounds as well as humification of stable ones. The sum of water soluble and bicarbonate phosphorus for matured C1 and C2 amounted to 5.2 and 7.4 g kg\(^{-1}\), respectively, and in relation to the other composts, the cited values were the highest (Table 5). For matured compost No.4 a higher amount of P was found in fractions I (by 16%), IV and V (2.0-fold), while a lower content of the element was recorded in fraction II (by 18%) (Table 5). It is worth noting that the high P content in the separated fraction was not associated with a high total P content. This phenomenon was found particularly in the case of C6 for the labile P pools obtained with water and bicarbonate. It was confirmed by the non-significant correlation coefficients (Table 6). In comparison to samples collected at the initial phase, matured composts Nos. 3, 5 and 6 were characterised by a lower P content in fractions I and II and higher in fractions III, IV and V, respectively. This is in agreement with the results of Ergrinya-Eneji et al. [23] and O’Connor et al. [24]. Such a direction of P changes may suggest that the more stable composts had lower extractable P amounts than unstable compost. Content of P in fractions I, II, III and IV increased during composting of mixtures for composts Nos. 1 and 2. At this same time, as a result of composting, residual phosphorus (Fr. V) decreased by 14% (C1) and 64% (C2) (Table 5). For matured compost No.4 a higher amount of P was found in fractions I (by 16%), IV and V (2.0-fold), while a lower content of the element was recorded in fraction II (by 18%) (Table 5).

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Table 5. Quantitative changes of phosphorus in fractions of composts in dependence on composting phase (g kg\(^{-1}\)).

| Composting phase | Fractions |
|------------------|-----------|
|                  | I  | II  | III | IV  | V   |
| Compost 1        | 1.51 | 1.90 | 3.54 | 0.20 | 0.43 |
| Initial          | 2.49 | 2.72 | 4.78 | 0.41 | 0.37 |
| Maturation       | 1.75 | 5.20 | 6.47 | 0.46 | 1.74 |
| Compost 2        | 1.88 | 5.53 | 9.29 | 1.88 | 0.62 |
| Initial          | 2.32 | 2.01 | 7.33 | 3.59 | 0.59 |
| Maturation       | 1.88 | 1.80 | 8.08 | 4.47 | 1.71 |
| Compost 3        | 0.65 | 0.87 | 8.54 | 0.86 | 0.18 |
| Initial          | 0.76 | 0.72 | 9.34 | 1.56 | 0.41 |
| Maturation       | 0.93 | 1.56 | 9.22 | 2.00 | 1.63 |
| Compost 4        | 0.74 | 1.71 | 9.58 | 2.48 | 2.15 |
| Initial          | 1.32 | 2.29 | 6.15 | 3.39 | 4.53 |
| Maturation       | 1.10 | 1.91 | 6.44 | 4.69 | 4.69 |
| LSD              | 0.226 | 0.299 | 0.764 | 0.295 | 0.50 |

34.7% (C6) to 77% (C4) in the initial phase. The composting process did not change this proportion significantly, because matured composts contained 34.2% (C6)–73% (C4) of P in fraction III. Generally the authors [17–19] showed the highest amounts of P associated with Ca. Studies conducted by this research group have indicated 18–30% of total P as unavailable forms (Fr. IV) and 8–30% of total P as organically bound. During P fractionation of compost investigators [5,20] reported that the least labile fraction of HCl-extractable P was found in the largest fraction and, together with the non-extractable residual P, reached more than 50–65%. Moreover Lü et al. [21] stated that, during composting of pig manure with rice straw the proportion of labile inorganic P decreased, while the proportion of Fe + Al-bound P, Ca + Mg-bound P and residual P increased. In this study a similar situation was observed only in the case of matured compost No. 6 (Figure 2). At the same time, according to the authors cited above the amount of the element in the readily available form (Fr. I) was assessed as 12–30% of total P. The conducted researches here showed that in matured composts the percentage share of P fraction I ranged between 4.5% (C5) and 23.2% (C1) (Figure 2).

Galvez-Sola et al. [6] and Wei et al. [22] maintained that the type and rate of phosphorus transformations during the composting process depended both on organic wastes used to prepare compost and the biotic decomposition of organic matter. The data presented in Table 5 and Figure 3 show that the composition of mixtures exerted a very strong influence on P content in separated fractions. The difference between the minimal and maximal values of mean amounts of this element for composting time was 3.0 (Fr. I), 7.0 (Fr. II), 2.0 (Fr. III), 13.0 (Fr. IV) and 15 times (Fr. V) (Figure 3). It is worth noting that the high P content in the separated fraction was not associated with a high total P content. This phenomenon was found particularly in the case of C6 for the labile P pools obtained with water and bicarbonate. It was confirmed by the non-significant correlation coefficients (Table 6). In comparison to samples collected at the initial phase, matured composts Nos. 3, 5 and 6 were characterised by a lower P content in fractions I and II and higher in fractions III, IV and V, respectively. This is in agreement with the results of Ergrinya-Eneji et al. [23] and O’Connor et al. [24]. Such a direction of P changes may suggest that the more stable composts had lower extractable P amounts than unstable compost. Content of P in fractions I, II, III and IV increased during composting of mixtures for composts Nos. 1 and 2. At this same time, as a result of composting, residual phosphorus (Fr. V) decreased by 14% (C1) and 64% (C2) (Table 5). For matured compost No.4 a higher amount of P was found in fractions I (by 16%), IV and V (2.0-fold), while a lower content of the element was recorded in fraction II (by 18%) (Table 5).
highest proportion of sewage sludge in composts Nos. 5 and 6 promoted phosphorus transformation into very stable, insoluble bonds, described by fractions IV and V. Evaluating the results of phosphorus sequential extraction it may be concluded that matured composts contain significant amounts of this nutrient, but its availability for plants varies.

The conducted analyses of the interdependence between total P content and its amounts in the separated fractions showed the strongest correlations for compost No. 1 at beginning as well as the end of the composting process (Table 6). Total P content highly correlated with the nutrient amount in all fractions only at the beginning of the composting process in the case of composts Nos. 2 and 5. Amounts of P in fractions of mature compost No. 3 were determined by the total content of this element in 96%. For composts Nos. 4 and 6 no significant correlations were found between the analysed parameters.

The application of stable and mature compost in agriculture can improve the soil structure by increasing...
**Figure 3.** Content of phosphorus in analysed composts fractions (mean values for composting time).

**Table 6.** Simple correlation coefficient values between total content of phosphorus and its amounts in separated fractions of composts at initial (I) and maturation (M) stage.

| Fraction | C1      | C2      | C3      | C5      |
|----------|---------|---------|---------|---------|
| I        | 0.960** | −0.968**| −0.915* | n.s.    |
| II       | 0.971** | −0.971**| 0.999** | n.s.    |
| III      | 0.968** | −0.964**| 0.938*  | n.s.    |
| IV       | 0.991** | −0.963**| 0.938*  | n.s.    |
| V        | −0.968**| 0.963** | −0.395* | n.s.    |

Note: n.s. – not significant, * and ** – statistically significant at the probability level 0.05 and 0.01 respectively; data obtained for C4 and C6 were not significant.
the soil organic matter content, suppressing soil-borne plant pathogens and enhancing plant growth.[25,26] However, immature compost may have adverse effects on plant growth and the environment because of the presence of phytotoxic compounds.[27–29] The application of bioassays is considered a sophisticated method to evaluate environmental pollution, supplementing chemical methods.[30] Among different tests, the germination of cress seeds was found to be both a rapid and sensitive indicator of substances strongly inhibiting germination and development of plants [25,28,31,32]. One may assume that information gained due to the GI facilitates an evaluation of the influence of phosphorus released from different wastes during the composting process on plants and the rate of future compost decomposition in soil. Moreover, inorganic P forms, such as orthophosphate or pyrophosphate, could also be assayed.[6]

For this reason the interdependencies between GI values (data not presented in this work) and phosphorus content in fractions I and II at the initial and maturation stages of composting were computed and presented as simple correlation coefficients in Table 7. It is worth mentioning here that independently of the composting stage most interdependencies were significant at the highest level of probability. Unfortunately, the obtained results are inconclusive and contradictory. The correlation coefficients in Table 7 show that amounts of P in fractions I and II may both inhibit and promote seed germination. It needs to be stressed that for immature composts Nos. 1, 4, 5 and 6 the amounts of P in the labile pool were negatively correlated with GI values. On the other hand, correlation coefficients obtained for immature compost Nos. 2 and 3 showed that the higher content of this element in fractions I and II enhanced the seed germination process. However, for matured composts the analysed variables were correlated negatively. The composting process resulted in GI values being determined by P in fractions I and II in 99% (C6) (Table 7).

### Soil load

Ongoing decline of organic matter in soils as a result of agricultural activities is a well-known phenomenon and is depicted as one of the main threats to the soil environment. The use of composted sewage sludge is a very important strategy and fulfils the postulate of the Thematic Strategy for Soil Protection.[33] When introducing organic matter to soil in the form of compost we have to consider the fact that simultaneously soil is enriched both ecologically and with nutrients, including phosphorus. The amounts, particularly P, need to be included in the total nutrient-balance so that any possible negative environmental impact may be avoided. This is informative not only in terms of the degree of soil enrichment in essential nutrients, but also in regard to their potential accumulation in soil. What is more, Fuentes et al. [34] concluded that compost application in intensive cropping system soils often exceeds P uptake owing to an accumulation of P species which are either unavailable or not readily available. Phosphorus accumulated in soil, depending on the character of its binding (physical or chemical) together with soil and climatic conditions, may be released in soil and chemically/physically transformed. Such derived forms may be leached into the soil profile or as a result of surface and subsurface runoff – penetrate to soil and open waters. In view of rational cultivation measures and environmental protection amounts of phosphorus may be estimated, which may theoretically be introduced to soils with the tested composts.

The estimated amounts of total and labile (fractions I and II) phosphorus, which would be added to soil using an application rate based on total nitrogen according to the threshold set by the Nitrates Directive (maximum input 170 kg N total/ha/yr), are presented in Table 8. The threshold of N applied as an organic fertiliser has an influence on P balance in soil. The fertiliser dose of 170 kg N/ha/yr may be associated with the amount of P, which is indicated in the higher content than P taken up by most crops.[2] Applying these permitted rates will thus generally lead to P accumulation in soil. Potentially the greatest amounts of element in total form may be introduced with C2 (165.2 and 180.0 kg for the initial and maturation phases, respectively), while the amounts are lowest for C6 (101.6 and 70.2 kg for the initial and maturation phases, respectively) (Table 8).

From the point of view of nutrient supplementation bioavailable amounts are crucial, covering the combinations of phosphorus directly available for plants (Fr. I), as well as those rapidly released in the soil medium
(Fr. II). As it results from Table 8, the lowest bioavailable amounts of P in fractions I (4.1–4.8 kg) and II (3.9–6.5 kg) might be introduced with C4. In turn, the greatest amounts of water soluble P may be introduced to soil with C1 (30.6–38.3 kg), while that of fraction II with C2 (52.0–55.0 kg). Taking into account amounts of P in sum of fractions I and II, from 8.0 to 80.2 kg might be incorporated into the soil with matured composts and from 11.3 to 73.5 kg with immature composts (Table 8). In the light of the recommended maximum application per year of 22–30 kg P per ha,[35] the values recorded in this study indicated that the analysed composts constitute an important source of this nutrient. However, the application of sewage sludge composts to soil needs to be performed with caution to prevent a negative environmental impact, connected with the accumulation of phosphorus in soil. In order to properly balance application rates and meet nutrient requirements of plants at a specific phosphorus level we need to have reliable data on the amounts of bioavailable nutrients in soil and in the fertiliser.

Conclusions

Conducted investigations showed that the analysed matured composts are valuable sources of phosphorus and should be considered as an alternative to mineral fertilisation. This was confirmed by data concerning total contents, as well as the amounts recorded in the sequentially isolated fractions of composts. Results from the sequential analysis of composts indicate that bioavailability of phosphorus in the main part depended on the character of combinations, formed by the nutrient with the solid phase of the composts and its composition. The applied composting process had a minor effect. Results indicate that the release rate of P from composts with a considerable share of sewage sludge (over 60%) is slower than that from composts containing small amounts of sewage sludge (max. 40%). Moreover, a factor determining this process may be connected with the different composting method. In the course of bioreactor composting of sewage sludge a stronger humification and stabilization of organic compounds was observed, including bound-phosphorus, which reduced its bioavailability for plants. In view of the above it may be assumed that such a compost would be a slower-release fertiliser: some nutrients will be released more slowly, thereby avoiding excessive amounts in soil. From the point of view of cultivation technology and environmental protection we need to treat with caution soil application of composts prepared with the lowest share of sewage sludge, since theoretically they may result in the introduction of 69.8 up to 80.2 kg bioavailable P per ha. These are considerable amounts for this nutrient, frequently exceeding the nutrient requirements of most crops and as was shown in this study – and they may have an adverse effect on plant germination.

In view of the above it is necessary to systematically monitor the quality of composts based on sewage sludge and to conduct long-term field trials using such fertilisers. We need to consider the fact that regardless of their chemical composition composts when introduced to soil undergo numerous processes, which depending on several factors may either increase or decrease the release rate of labile phosphorus forms, and may lead to their accumulation in soil. Thus comprehensive analyses are required, assessing resources of available phosphorus both in composts and in soils fertilised with these composts, to ensure that such supplementation is consistent with the principles of sustainable fertilisation and environmental protection.

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| Table 8. Estimated annual phosphorus input rates (kg/ha) to soil from composts applied at 170 kg N total/ha. |
|---------------------------------------------------------------|
| Compost | P total | P fraction I | P fraction II | P in sum of fraction I and II |
|---------|---------|--------------|--------------|------------------------------|
| I       | M       | M            | M            | M                            |
| 1       | 153.4   | 165.4        | 30.6         | 38.3                         | 38.5                         |
| 2       | 165.2   | 180.0        | 18.5         | 17.8                         | 55.0                         |
| 3       | 107.1   | 102.6        | 13.6         | 10.8                         | 15.7                         |
| 4       | 82.6    | 68.8         | 4.8          | 4.1                          | 6.5                          |
| 5       | 111.4   | 69.3         | 6.8          | 7.1                          | 11.3                         |
| 6       | 101.6   | 70.2         | 7.6          | 4.1                          | 13.1                         |

CHEMICAL SPECIATION & BIOAVAILABILITY 197
