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ORIGINAL PAPER

Amounts of nutrients from plant residues supplied into the soil after oilseeds harvesting*

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Abstract

Increasing demand for sustainable production stimulates more efficient use of local resources in agricultural production. Both aerial (stubble) and underground (roots) plant residues left in the field after harvesting a crop are one of such sources. This study quantifies the share of nutrients (N, P, K) in plant residues after the harvest of four different oil crops (sunflower, raps, soybean, and mustard) in seven soil and climate heterogeneous regions of Slovakia during a nine-years period. The results showed that winter oilseed rape and mustard left the most residues in the soil (more than 10 tons of dry biomass per hectare). After harvesting the sunflower, 5-10 tons of plant residues remained in the soil, and soybeans left the least residues (less than 5 t ha^{-1}). These data and the content of nutrients in plant residues are the base for deriving a coefficient of nutritional potential in the calculations by polynomial regression, i.e. the amount of nutrients that remains after harvesting per one ton of the main product. These coefficients and the known yield of a given crop allow us to calculate how much of a given nutrient each crop will leave in the soil after its harvest. The results showed that the amount of remaining nitrogen in plant residues ranges from 91 to 132 kg, phosphorus from 14 to 22 kg and potassium from 72 to 218 kg ha^{-1}. The above findings must be considered when calculating the need for fertilizers for the following crop, to reduce the risk of environmental pollution, especially with excess nitrogen.

Keywords: aerial plant residues, underground residues, oil plants, nutrient potential coefficient

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INTRODUCTION

Low species diversity in current agricultural practice is a generally recognized shortcoming of plant production. This must then rely on the supply of nutrients from external sources, especially in the form of mineral fertilizers. A much more rational alternative nutrient recycling is to return the residues of cultivated crops back to the soil. It is with them that not only organic matter is supplied to the soil, which improves the quality of the soil, but also considerable amounts of nutrients (especially nitrogen, phosphorus, potassium, calcium, and magnesium, but also micronutrients) enrich the soil. In addition to the supply of nutrients to the soil, it should also be mentioned that nitrogen from plant residues is leached from the soil to a significantly lesser extent than from applied mineral fertilizers (Sugihara et al. 2012, Smith et al. 2021, Frerichs et al. 2022), which also affects the quality of groundwater (Aulakh et al. 2000). Plant residues, left on the soil after the harvest of the main product, limit the loss of water by evaporation and prevent both water and wind erosion of the soil (Cook 2006), as well as overall soil degradation (Vilček et al. 2019).

The return of plant residues (both post-harvest and root) that remain in the field after harvesting the main harvest of field crops to the soil is a technically undemanding agrotechnical procedure, which is friendly to the natural environment and which, at the same time, brings not only ecological but also economic benefits.

Each plant species contains different amounts of nutrients, which arises from genetic differences (Chen et al. 2014). The content of nutrients in plants is also influenced by fertilization, variety, soil moisture, climate change and, to some extent, agrotechnical operations. But the common factor is that nitrogen and potassium are represented in the largest amounts among nutrients. When plant residues decompose in the soil, they become available to the following crops. The rate of decomposition of plant residues depends on the C/N ratio in them. If the C/N ratio is less than 40, the rate of decomposition is higher than in plants with a C/N ratio higher than 40 (Baldock 2007).

From the point of view of plant nutrition as part of crop rotation, information on the amount of nutrients in plant residues is very important. This applies primarily to organic farming. The aim of this paper was to propose a simple model that could be used to calculate the amount of nutrients that can enter the soil from the decomposing plant residues of the previous crop. We focused on the most cultivated oil crops, i.e. sunflower, winter rape, soybean, and mustard. Data on the yield of the main product of cultivated oilseeds and their coefficient of nutritional potential were used in the creation of the model.

MATERIALS AND METHODS

During a nine-year period in seven different soil and climatic condition in Slovakia (Table 1), post-harvest aerial (stubble) and underground (root) residues of the most cultivated oilseeds: sunflower (*Helianthus annuus* L.), winter rape (*Brassica napus, subsp napus* L.), soybean (*Glycine max L.* Merrill) and mustard (*Sinapis alba* L.) were analyzed.

Table 1

Location, soil, and climate conditions of experimental sites

Locality	Geographic coordinates	Altitude (m)	Soil type	Average annual rainfall during observed period (mm)	Average annual temperature during observed period (°C)
Kravany nad Dunajom	47°45′N; 18°29′E	106	Calcaric Fluvisol	548	10.6
Rišňovce	48°21′N; 17°54′E	173	Haplic Luvisol	531	10.1
Gbely	48°43′N; 17°07′E	205	Haplic Chernozem	585	10.6
Nemšová	48°58′N; 18°07′E	206	Eutric Fluvisol	619	9.2
Lovonobaňa	48°25N; 19°35′E	265	Stagnic Glossisol	720	8.6
Divín	48°27′N; 19°31′E	290	Eutric Cambisol	720	8.6
Bodovce	49°07′N; 21°11′E	462	Stagni Cambisol	644	8.1

The number of observations at all locations for the whole monitoring period was 27 in the case of winter rape, 13 in the case of sunflower, 9 in the case of mustard and 11 in the case of soybean.

Data on average annual precipitation and temperatures were taken from the nearest meteorological stations of the Slovak Hydrometeorological Institute.

The yield of each crop was determined as the average of three randomly selected squares of one square meter from fields ranging in size from one to five hectares and finally expressed in t ha^{-1}.

The amount of plant residues was determined from the same sampling points. The sampling area of underground and aerial residues depended on the growing system of a given crop (number of individual plants per hectare) and was as follows: sunflower 0.7 m × 0.3 m, soybean 0.4 m × 0.25 m, mustard and winter rape 0.25 m × 0.25 m. The quantity data were converted to an area of one hectare. Aerial residues represented the mass of stubble that remained after the harvest of the given crop. They were cut with scissors from the same area immediately before taking the roots. Root residues were collected from a soil depth of 0.0-0.3 m in the months of July to October, depending on the cultivated crop and climatic conditions. Root residues were collected with soil in three replicate samples from the same locations as post-harvest residues. Soil was removed by passing the samples through a set of 1 mm, 0.5 mm, and 0.25 mm mesh sieves. All unnecessary material except the roots was removed, first by repeated decanting and finally by manual separation. The underground and aerial residues of all crops were dried, ground, and subsequently analysed for three basic macronutrients (nitrogen, phosphorus, and potassium in elemental form) using the following methods:

– nitrogen colorimetrically after wet burning with sulfuric acid (according to Kjeldahl ISO 11261:1995),
– phosphor spectrophotometric according to ISO 11263:1994 on a Spekol 11 device (Carl Zeiss Jena),
– potassium using emission flame photometry after wet burning with a mixture of nitric and perchloric acid (Javorský et al. 1987).

The nutritional potential coefficient was determined as the amount of nutrients in kg per one ton of the main product. The term "nutrient potential" refers to the average amount of nutrients (nitrogen, phosphorus, and potassium), expressed in kg per hectare, present in the aerial and below-ground residues of the harvested crop at the time they are ploughed back into the soil. The nutritional potential coefficient for the crops we monitored was calculated by statistical analysis of the experimental results using polynomial regression. The regression equation for each determined coefficient (K_N, K_P and K_K) was calculated from the actual measured yield in the given area using MS Excel® (2016). The degree of the polynomial equation was chosen based on obtaining the highest possible correlation coefficient. According to the results of the polynomial regression, these correlations between the yield and the value of the coefficients are highly significant (r=0.812-0.995, at * P<0.05).

Using the values obtained for the coefficients, it was possible to calculate the inputs of nitrogen, phosphorus, and potassium from plant residues to the soil using the following equation:

$$P_X = u \cdot K_X,$$

where: P_X – amount (kg ha^{-1}) of nutrients (N, P, K) in plant residues of the given crop;

u – yield of main product (t ha^{-1}) (with normal or optimal moisture content at harvest);

K_X – value of the nutritional potential coefficient of the given crop (K_N, K_P, K_K).

RESULTS AND DISCUSSION

Various types of oilseeds produce different amount of plant residues. The mass of aerial and underground residues is mainly determined by the biological differences between individual plant species. Even within the same crop, there can be considerable variability. Among the monitored oil crops, the most residues were produced by the winter rape (14.32 t ha^{-1}), and the least by soybean (3.89 t ha^{-1}) – Table 2. The highest share of aerial residues from the total amount of plant residues is left by mustard (80%) and the smallest share is by soybean (62%).

Table 2

Yield of observed oil crops, mass of belowground (root) and aboveground (stubble) residues of total crop residues

Crop	Average yield of main product	Plant residues total	Aerial residues	Below-ground residues
	(t ha^{-1})			
Sunflower	2.17	8.78	6.78	2.00
Winter raps	2.57	14.32	11.20	3.12
Soybean	1.92	3.89	2.41	1.48
Mustard	2.01	10.18	8.20	1.98

According to the determined average amount of dry matter of root and post-harvest residues, it is possible (also considering the method of their cultivation, i.e. ploughing of the entire by-product crop) to state that:

– a **rich source of plant residues** is both winter rape and mustard, during the cultivation of which the entire crop of their straw is ploughed into the soil, thanks to which more than 10 t ha^{-1} of plant residues reach the soil after harvest;

– a **significant source of plant residues** is the sunflower, after harvesting, an average of 5.0 to 10.0 t ha^{-1} of plant residues remains in the soil;

– a **less abundant source of plant residues** is soybean – after the harvest of its main product, on average less than 5 t ha^{-1} of plant residues reach the soil.

Already in our previous works (Jurčová, Torma, 2001) we declared that the total amount of nutrients in plant residues is highly variable. It depends not only on the biological differences between individual types of crops and the amount of produced post-harvest aerial and underground residues, but also on the content of individual nutrients in these residues, the yield of cultivated crops and in some cases also from various agricultural practices (for example the intensity of fertilization). For the nutrients we monitored (nitrogen, phosphorus, and potassium), their total concentration in the residues varied relatively significantly, when, for example, the difference between the highest and lowest nitrogen content in the plant residues of the studied oil crops was 45%, in the case of phosphorus 57% and in the case of potassium even up to 303% (Figure 1). There are also differences in the content of nutrients in the underground and aerial parts of the same plant: the nitrogen content is usually higher in the root residues; the potassium content is always higher in the post-harvest residues. Phosphorus biologically accumulates in generative organs and only slightly in vegetative

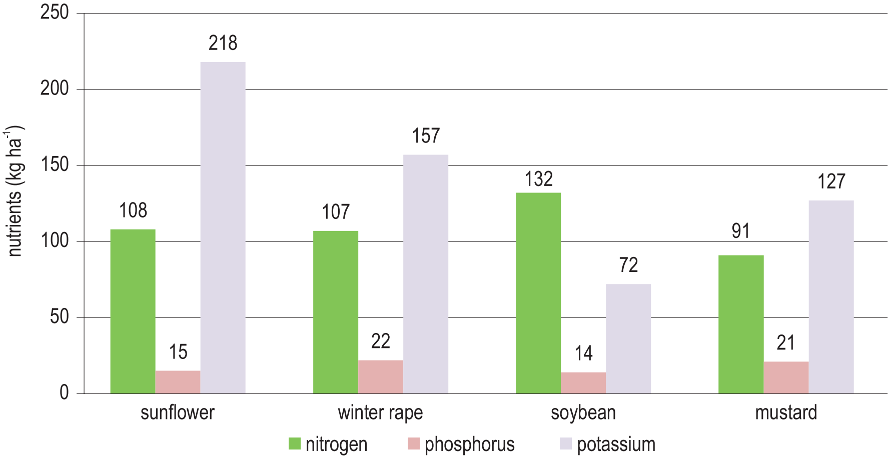

Fig. 1. Content of nitrogen, phosphorus, and potassium in post-harvest residues (average value in kg ha^{-1})

organs, therefore the potential of this nutrient in the residues of individual crops is mostly small.

The amount of nitrogen left in the soil in the plant residues of the monitored oil crops ranged from 91 kg (mustard) to 132 kg (soybean), the amount of phosphorus from 14 kg (soybean) to 22 kg (winter rape), and the amount of potassium from 72 kg (soybean) to 218 kg ha^{-1} (sunflower). The mentioned amounts of plant residues and their management naturally affect the quality of the soil, either directly or indirectly. Intensive cropping systems are highly diverse and complex, and ideally plant residue management practices should be chosen to increase crop yields with minimal adverse effects on the environment (Kumar, Goh 1999). The amount of all monitored nutrients in the plant residues of oilseeds is much higher than, for example, in the residues of cereals, while in the case of nitrogen and phosphorus it is two to three times higher and in the case of potassium it is even four to five times higher (Jurčová, Torma 2001). There is an even more significant difference when we compare oilseeds with root crops, for example, sugar beet plant residues contain only 20 kg of nitrogen, 2 kg of phosphorus and 13-15 kg of potassium ha^{-1} of land (Torma, Vilček 2017).

It is widely known that the input of organic residues by crops into the soil can improve its overall fertility (Partey 2011, Babu et al. 2014, Blesh, Ying 2020, Liu et al. 2022). However, not all plant residues fulfil this purpose. Partey et al. (2013) documented problems with delayed decomposition of corn residues left on the soil due to short-term nitrogen immobilization, as soil nitrogen availability varies with the amount of nitrogen mineralized or immobilized during crop residue decomposition (Li et al. 2017). Conventional crop fertilization practices and recommendations usually ignore the amount of nitrogen that will be mineralized from decomposing plant residues (Vigil, Kissel 1991).

When crops are harvested, the plant residues remaining on and in the soil do not release much nitrogen into the soil in the first year of decomposition, but the nitrogen stored in the soil is probably released only in the following years (Lupwayi et al. 2006), although this statement is negated by Matos et al. (2011), who declare that approximately 32% of the total amount of nitrogen in the plant material is released within the first 15 days. According to these authors, the fastest released nutrient from plant residues is phosphorus.

The statistical evaluation of our results showed that there is a non-linear correlation between the height of the harvest of the main product and the amount of nutrients from plant residues of each of the monitored crops. We used the given knowledge to determine the coefficients expressing the ratio of nutrients from plant residues to the yield of the main product. These coefficients, denoted as K_N for nitrogen, K_P for phosphorus and K_K for potassium, represent the amount of nutrients in kg ha, corresponding to 1 ton of the main product yield from 1 ha of land.

However, the determined values of the coefficients for the conversion of nutrients are not constant but change according to the height of the crops. Figures 2-5 present a non-linear correlation between the amount of nutrients in the post-harvest residues and the yield of the main product of the observed oil crops. Although the values of the coefficients increase with increasing harvests, it should be emphasized that this trend is neither linear nor continuous. The coefficients rise only up to a certain threshold of harvests, at which they stagnate and after exceeding it, they begin to decrease. This knowledge about the variability of coefficients for the conversion of nutrients is important if for some purposes the most accurate data on the input of nutrients to the soil in the form of post-harvest and root residues of a certain crop is needed.

The regression equations for each observed nutrient (K_N, K_P and K_K) were calculated from the actual yield achieved on the given field. The degree of the polynomial equation was chosen to achieve the highest degree of correlation. According to the results of the polynomial regression, these correlations between the height of the crops and the value of the coefficients are highly significant (r=0.826-0.963, at * P<0.05).

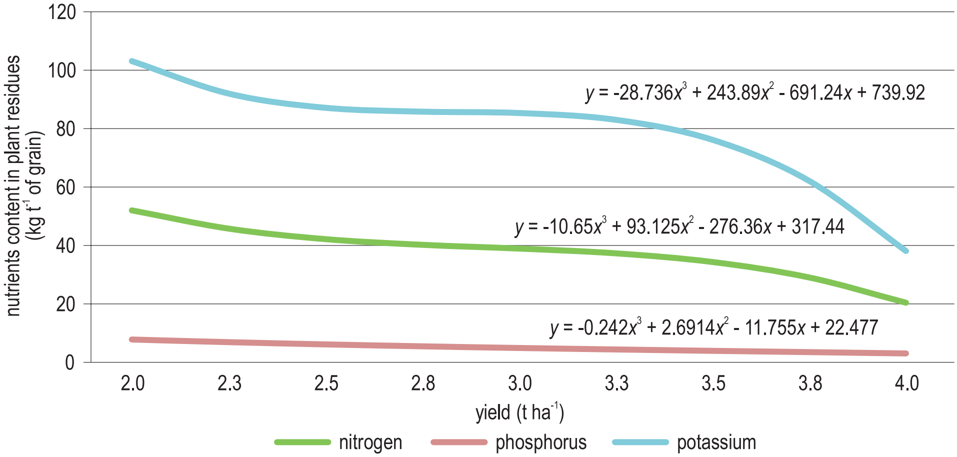

Fig. 2. The amount of nutrients (N, P, K) in the plant residues of sunflower (in kg t^{-1} of the main product) as a function of the yield of the main crop (the given data represent average values for the whole of Slovakia)

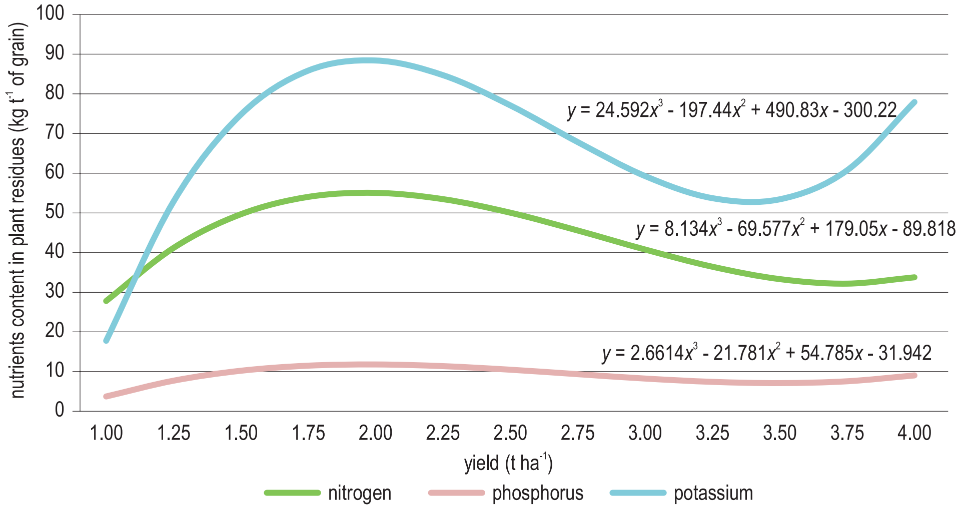

Fig. 3. The amount of nutrients (N, P, K) in the plant residues of winter rape (kg t^{-1} of the main product) as a function of the yield of the main crop (the given data represent average values for the whole of Slovakia)

In the model developed in this study, the total amount of nutrients in plant residues was calculated as described below, using the example of sunflower with a grain yield of 3.0 t ha^{-1}. According to the equation in the table ($K_N = 8.1346x3 - 69.577x2 + 179.05x - 89.818$; where x = crop yield), it follows that the KN coefficient for winter rape is 40.7732. The next step was the calculation of PN (amount of nitrogen in winter rape residues in kg ha^{-1}) using the equation: $P_N = u \times K_N$ (where u is the grain yield and KN is its corresponding coefficient). For example, with a crop yield of 2.50 t ha^{-1}

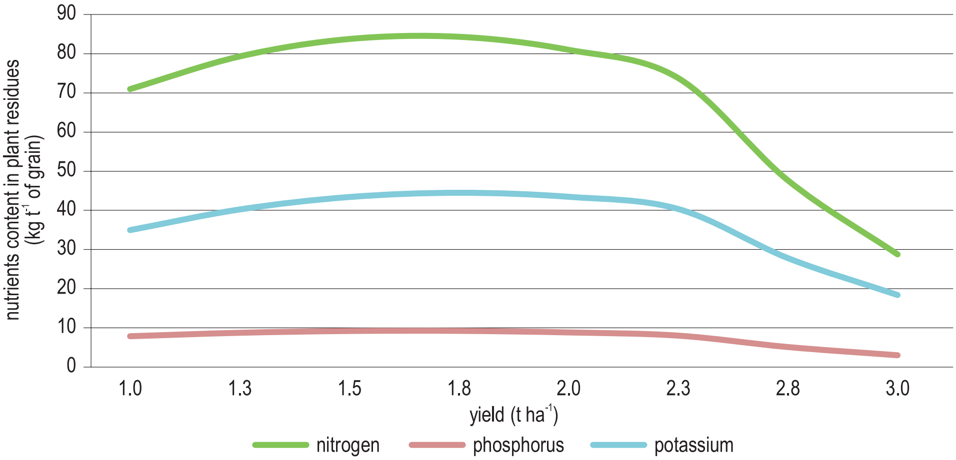

Fig. 4. The amount of nutrients (N, P, K) in the plant residues of soybean (kg t^{-1} of the main product) as a function of the yield of the main crop (the given data represent average values for the whole of Slovakia)

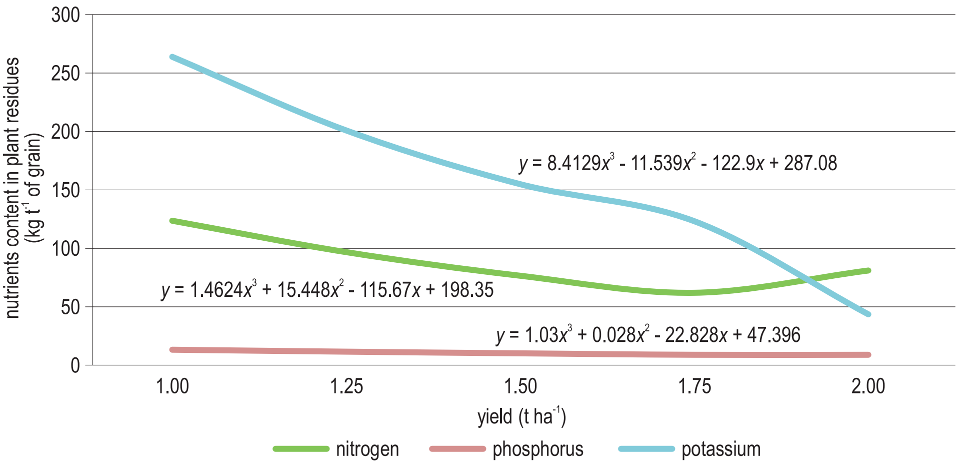

Fig. 5. The amount of nutrients (N, P, K) in the plant residues of mustard (kg t^{-1} of the main product) as a function of the yield of the main crop (the given data represent average values for the whole of Slovakia)

(2.50 × 40.7732 = 101.9 kg of nitrogen), 101.9 kg of nitrogen will remain in the soil for the next cultivated crop after harvesting winter rape. The same method was used in the calculations for the other nutrients (phosphorus and potassium) and for all other investigated crops. Table 3 lists the amount of nutrients in the ploughed plant residues of some crops at normally achieved yields.

It is clear from Table 3 that the amount of nutrients (especially nitrogen and potassium) left in the soil after harvesting a specific crop is not negligible. For example, with an average sunflower yield of 3.0 t ha^{-1}, this crop

Table 3

The amount of nitrogen, phosphorus and potassium ploughed into the soil in plant residues of oil crops at normally achieved yields

Crop	Yield potential (t ha^{-1})	Content of nutrients (kg ha^{-1})		
		nitrogen	phosphorus	potassium
Sunflower	2.5 3.0 3.5	105.4 116.8 120.2	15.3 14.7 13.8	217.8 256.0 266.6
Winter rape	2.0 3.0 3.5	110.1 122.3 135.1	23.6 24.7 36.1	176.8 177.9 311.8
Soybean	1.5 2.0 2.5	125.6 162.0 156.6	13.8 17.7 17.0	62.1 86.9 87.8
Mustard	0.5 1.0 1.5	72.3 99.6 97.8	18.1 25.6 25.0	111.9 1614.1 157.7

leaves more than 100 kg of nitrogen and more than 250 kg of potassium in the soil. Even more nitrogen remains after harvesting soybeans (more than 160 kg at a yield of 2.0 t ha^{-1}). As mentioned above, at least 50% of the nutrients left in plant residues are available for the next crop grown. This means that about 60-80 kg of nitrogen and 100-120 kg of potassium is available in the soil for the following crop without any additional fertilization. This must be considered when determining the doses of mineral fertilizers applied under the following crops to use resources more efficiently, and thus reduce the risk of eutrophication as well as improve the profits of agricultural enterprises by reducing of applied fertilizers. This model can also be used in the conditions of ecological agriculture, water protection of a specific area, or in areas with strong nitrogen transport in soils (Torma et al. 2019) and when farming in protected nature reserves. It brings not only an economic but also an environmental benefit compared to conventional fertilization and contributes to sustainable agriculture.

CONCLUSIONS

Based on the presented long-term experimental results, it can be concluded that the post-harvest and root residues of some field crops are, due to their nutrient potential, an important part in the biological cycle of substances. They play a positive role in the balance of nutrients in the crop rotation, in the nutrient regimes of soils, and thus also in nutrition of subsequently cultivated crops. However, the potential of the content of nitrogen, phosphorus, potassium, but also magnesium and calcium in plant residues is quite different and depends primarily on the biological characteristics of the plant species and on the yield of the given crop. In the case of monitored oil crops, the amount of nitrogen left in the soil with plant residues ranged from 91 kg (mustard) to 132 kg (soybean), the amount of phosphorus from 14 kg (soybean) to 22 kg (winter rape) and the amount of potassium from 72 kg (soybean) up to 218 kg ha^{-1} (sunflower). Based on these data, the farmer has the opportunity to optimize the fertilization of subsequent crops, which contributes to the protection of individual components of the environment (soil, water), but also to saving costs for growing crops. The model presented in the work presents potential assumptions for determining the amount of nutrients in plant residues. The assumption of their usability by subsequently grown crops can be the subject of further experiments and verifications.

The coefficients for the conversion of nutrients and the mathematical model, based on which it is possible to calculate the input of nutrients in the form of plant residues into the soil, have a high application potential in the balance of nutrients in a crop rotation system. It can also be used in the plant nutrition in the conditions of the biological (ecological) system of soil management, in zones of hygienic protection of both underground and surface water sources, in protected areas, state nature reserves, etc.

Author contributions

S.T, J.V. – conceptualization, S.T, J.V. – formal analysis, S.T. – methodology, S.T. – investigation, J.V., W.S., B.R.– visualisation, S.T, J.V. – writing, original draft preparation, S.T, J.V., W.S., B,R. – writing, review and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest. The authors ensure that they have neither professional nor financial connections related to the manuscript sent to the Editorial Board.

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