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Impact of NPK fertilization in agricultural reclamation on the transformation of Technosols in post mining area: a case study from the Konin open-pit brown coal mine, central Poland

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Abstract

The study assessed the effect of long-term, diversified NPK fertilization and cereal monoculture on the physical and water properties of post-mining Technosols. The research was carried out in 2022 at an experimental plot established in 1978. A field experiment was established on the internal heap of the Pątnów KWB Konin (Brown Coal Mine Konin). In the research area, since the beginning of the experiment to the present day, an annual cereal crop rotation has been cultivated (winter rye alternating with winter wheat). In 1988, the area was divided into three experimental sections that received different rates of NPK fertilization. The study area consisted of three plots – marked in the paper as: 0 NPK, 1 NPK, 2 NPK. In each section the morphology of three soil profiles were described. From each genetic horizon, samples with a disturbed and intact structure were collected. The results of the analyzes were treated as repetitions and statistically processed. The collected material was used to analyze the basic physical, water and chemical soil properties. The tested soils were classified as Spolic Technosols (Pantocalcaric, Katodensic, Pantoloamic, Ochric). Mineral fertilization improved the physical and water properties in the surface horizons, but no effect was observed on subsoil properties. Fertilization with a single NPK application was found to be effective and additional applications were considered superfluous.

1. Introduction

Opencast mining of lignite leads to significant changes in the soil cover, and the area affected may encompass several hundred hectares (Kozłowski et al., 2023). These transformations concern not only the soil, but also entail unfavorable hydrological changes in the deeper horizons of the lithosphere (Ahirwal and Maiti, 2016) with the result that large areas require reclamation. One such an example is the post-mining land of the Konin Industrial Area in Central Poland (Otremba et al., 2013), where reclamation is mainly determined by the nature of the bedrock. It is a type of conglomerate composed of Quaternary formations – sands and boulder loams mixed together in various amounts (Gilewska and Otremba, 2005). While the soil properties are important for the soil-forming processes that take place in such soils, the type of reclamation treatment employed also co-shaping the properties of the developing soils (Gilewska and Otremba 2005). This was observed in the early 1970s, when the most important assumptions for the reclamation of post-mining areas were developed – hereafter referred to as the PAN model (Bender, 1995). In the PAN model the focus was on three main activities: repair of the "barren soil-rock" chemistry (through NPK fertilization), repair of the physical properties (by ploughing), and introduction of crops (mainly alfalfa, rapeseed and cereals). The use of NPK fertilization is dictated by the low content of nitrogen and phosphorus in such materials (Kołodziej et al., 2017), and the introduction of plants is intended to increase the organic carbon content. The low content of the latter in post-mining soils has been reported by e.g. Greinert et al. (2018). This is important not only in the context of restoring the productive function of these soils, but also in reducing (carbon dioxide) CO_2 emission into the atmosphere (Otremba et al., 2020). The bioaccumulation role of plants during the reclamation of post-mining areas has also been noted (Feng et al., 2019), while Zhao et al. (2013) associated it with a positive impact on soil biodiversity. The described synergistic action provides rapid results, as the post-mining land acquires the characteristics of soil after about 10 years (Feng et at., 2019; Peco et al. 2021). In this study we assessed the effect of long-term, diversified NPK fertilization and cereal monoculture on the physical and water properties of post-mining areas. Our hypothesis was that agricultural reclamation would improve the soil conditions for plant development.

2. Materials and methods

The research was carried out in 2022 at an experimental plot established in 1978 that belongs to the Department of Soil Science, Reclamation and Geodesy of the University of Life Sciences in Poznań in Poland. The aforementioned field experiment was set up on the internal heap of the Pątnów KWB Konin (Brown Coal Mine) opencast (52°18'41.13''N, 18°15'39.19''E, Fig. 1). Research on the productivity of post-mining land has received considerable attention and has ranged from theoretical assumptions, field experiments, soil and plant analysis, development of practical solutions, and their application in reclamation practice (Bender, 1995). An element of these works was an experimental plot, which was the object of work research. From the start of the experiment to the present day an annual cereal crop rotation has been cultivated (winter rye alternating with winter wheat) in the research area. For the first 10 years, NPK fertilization was dependent on the chemical, physicochemical andsorption capacity of the soil being formed, as well as the nutritional needs of crop species (Bender and Gilewska, 2004; Spychalski et al., 2008). In 1988, the plot was divided into three experimental plots which received different rates of NPK fertilization. For wheat: 0 NPK (control – without fertilization), 1 NPK (160 N, 40 P_2O5, 80 K_2O kg ha^{-1} yr^{-1}), 2 NPK – doses twice as high as 1 NPK) and for rye 0 NPK (control – without fertilization), 1 NPK (130 N, 60 P_2O_5, 100 K_2O), 2 NPK – doses twice as high as 1 NPK. Three soil profiles were created in each plot (Fig. 1). From each soil horizon (in each of the nine soil pits) one composite bulk sample with a disturbed structure and eight core samples (100 cm^3) with undisturbed structure were taken. The results of the analyzes were treated as repetitions and were statistically processed. Therefore, the properties given in the tables for each of the three plots come from three soil profiles (nine in total).

The collected material was used to evaluate the following soil properties: particle size distribution, using the Cassagrande method modificated by Prószyński (Mocek et al., 2022); particle density (PD), using the pycnometer method (Blake and Hartge, 1986); bulk density (BD), using metal cylinders of known volume (100 cm^3); total porosity (TP) was calculated on the basis of the determinations of particle density and bulk density (Mocek et al., 2022); organic matter content (OMC), as loss of ignition at 550°C (Grimshaw et al., 1989); reaction of the soil (at 1:2.5) using H_2O and 1M KCl as a suspension medium, maximum hygroscopic capacity (MH – moisture content at pF 4.5) was determined in a vacuum chamber at 0.8 atm. with a potassium sulphate (K_2SO_4) saturated solution (Mocek et al., 2022); soil water potential using the Richards pressure chamber method (Klute, 1986); total available water (TAW) and readily available water (RAW) were calculated on the basis of pF determinations (Mocek et al., 2022). All results presented here are the mean values of three replications. In order to determine the statistical significance of the differences between the factor levels, a two-factor analysis of variance with interaction was performed. The assumption of homogeneity of variance was tested with the Levene test (Levene,1960; Zimmerman, 2004), and the normality of the distribution of residuals from the model – with the Shapiro-Wilk test (Shapiro and Wilk, 1965). If the assumptions were not met, the raw data were transformed by the Box-Cox method (Box and Cox, 1964). Significance of differences between fertilization variants was checked using Tukey's pairwise comparisons test. The significance of Pearson's correlation between soil parameters

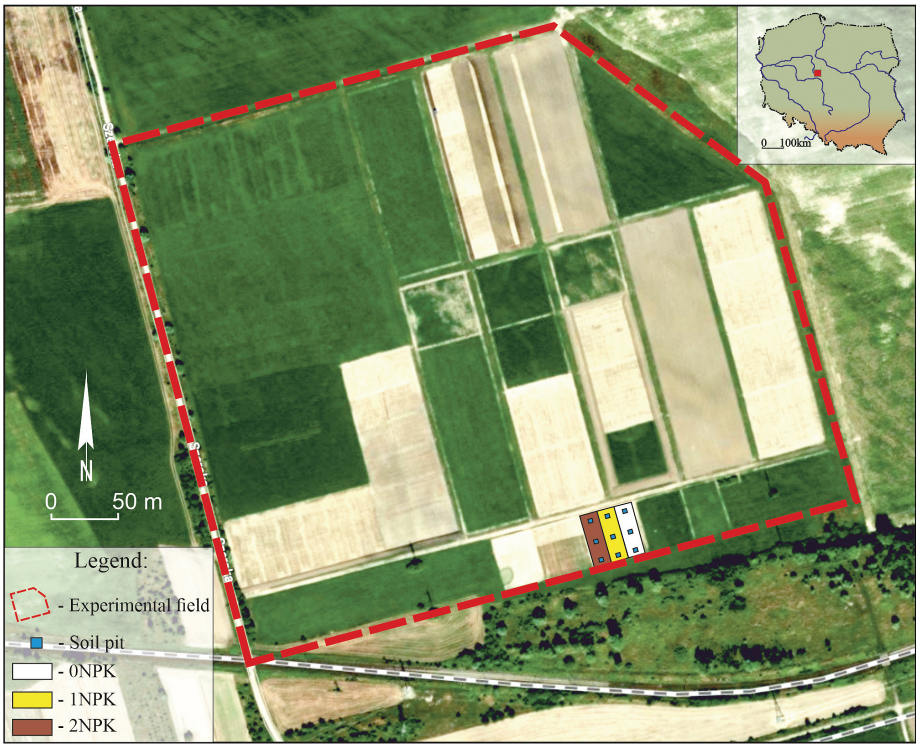

Fig. 1, Location of examined points

was checked. Cluster analysis was performed using the Manhattan distance and Ward's linking method (Ward, 1963). In all statistical analyses, the significance level α = 0.05 was adopted. The calculations were made using the following packages: stats (R Core Team, 2021), multcomp (Hothorn et al., 2008), MASS (Venables and Ripley, 2002) and car (Fox and Weisberg, 2019) from the R computing platform.

3. Results

The tested soils were classified as Spolic Technosols (Pantocalcaric, Katodensic, Pantoloamic, Ochric; IUSS Working Group WRB, 2022). The epipedons (Ap) and endopedons (Cd1; Cd2) were clearly developed. The parent material and the arable-humus horizon formed from it, consisted of boulder loam from the Warta glaciation (Riss 2, Saale- Warthe). The particle size distribution was very similar within all fractions. The sand content in the Ap horizons ranged from 66 to 68%, and ranged from 65 to 74% in the endopedons. The clay content in the Ap horizons was (11–12%), whereas in the epipedons (10–14%). The silt content ranged from 15 to 23% (Table 1). Among the size fractions no statistically significant differences were found and all genetic horizons had a texture of loamy sand (Soil Survey Division Staff, 1993). The homogeneity of particle size distribution was a key feature in assessing the influence of experimental factors on the tested features.

Soil BD in the individual profiles was significantly different for Ap horizons and ranged from 1.51 t m^{-3} in the 2NPK plot – to t m^{-3} in the 0 NPK plot. In all cases, the endopedons' density was significantly higher than of Ap horizons. It ranged from 1.80 to 1.81 t m^{-3} in the control combination (0 NPK) and from 1.75 to 1.79 t m^{-3} in the fertilized variants. The values of this characteristic were aligned within the Cd1 and Cd2 horizons (Table 2). Total porosity, which is essentially a mirror reflection of soil density in such a homogenous material showed the opposite trend. In the analyzed soils, it ranged between 34.1–42.6% v. in the Ap horizons and between 31.7–34.0% v. in the Cd horizons (Table 2). Both of these properties were moderately correlated with the OMC (Table 3).

Table 1
Particle size distribution of examined soils

Fertilization variant	Horizon	Depth (cm)	Fraction (%)			Soil textural class (USDA)
			Sand 2–0.05 mm	Silt 0.05–0.002 mm	Clay <0.002 mm	
0 NPK	Ap	0–26+/–2	68	21	11	SL[1]
	Cd1	26–67+/–3	67	19	14	SL
	Cd2	67–94+/–4	74	15	11	SL
1 NPK	Ap	0–25+/–2	67	21	12	SL
	Cd1	25–73+/–4	65	21	14	SL
	Cd2	73–96+/–5	68	20	12	SL
2 NPK	Ap	0–26+/–3	66	23	11	SL
	Cd1	26–71+/–6	67	21	12	SL
	Cd2	71–97+/–5	73	17	10	SL

SL[1] – sandy loam

Table 2
Selected physical and chemical properties of examined soils

Fertilization variant	Horizon	Depth (cm)	Bulk density (t m^{-3})	Total porosity (%v.)	Organic matter content (%)	pH in H_2O	pH in 1M KCl
0 NPK	Ap	0–26+/–2	1.74c	34.1b	1.74ab	8.36bcd	7.71ab
	Cd1	26–67+/–3	1.81d	31.7a	1.40a	8.09a	7.71ab
	Cd2	67– 94+/–4	1.80cd	32.1ab	2.16bc	8.19ab	7.71ab
1 NPK	Ap	0–25+/–2	1.53a	42.1d	2.46c	8.3bc	7.63ab
	Cd1	25–73+/–4	1.77cd	33.2ab	1.73ab	8.42cd	7.65ab
	Cd2	73–96+/–5	1.79cd	32.7ab	1.88b	8.41cd	7.56a
2 NPK	Ap	0–26+/–3	1.51ab	42.6de	2.47c	8.27abc	7.53a
	Cd1	26–71+/–6	1.75cd	34.0ab	1.35a	8.55d	7.77b
	Cd2	71–97+/–5	1.75cd	34.0ab	1.42a	8.55d	7.71ab

α = 0.05/values marked with the same letters do not differ significantly

Table 3
Correlation coefficients between selected properties

1	—							
2	**0.92**	—						
3	**0.57**	**0.68**	—					
4	**0.33**	**0.53**	**0.59**	—				
5	–0.04	**–0.43**	**–0.40**	**–0.53**	—			
6	**–0.60**	–0.70	**–1.00**	**–0.59**	**0.41**	—		
7	**–0.02**	**–0.07**	0.06	–0.29	0.11	–0.06	—	
8	–0.48	**–0.48**	–0.27	**–0.51**	0.10	0.28	0.31	—
	1	2	3	4	5	6	7	8

Explanation: 1 – RAW, 2 – TAW, 3 – Total porosity, 4 – Organic matter content, 5 – RAW/TAW, 6 – Bulk density, 7 – Maximum hygroscopic capacity, 8 – pH 1M KCl
Significant correlations are highlighted in bold (α < 0.05)

In the Ap horizons OMC ranged from 1.74 to 2.47%. Both fertilization plots were exhibited similar values (2.46–2.47%) and were significantly higher than the control (1.74%). Except for the 0 NPK variant, the OMC was significantly higher in Ap horizons than in Cd. In the 1 NPK and 2 NPK plots, the differences in OMC in the Cd horizons were not statistically significant (Table 2). In addition to the above-mentioned correlation with BD and TP, OMC correlated significantly and positively with RAW, TAW and negatively with RAW: TAW and pH_{KCl}. The strength of these correlations was low or medium (Table 3). The pH_{KCl}, determined to supplement the soil characteristics, ranged from 7.53 to 7.77 (Table 2). No statistically significant differences were observed between pH_{KCl} in the surface horizons and parent material horizons.

At field water capacity (FC, pF 2.0), the tested soils retained between 29.10 to 35.07% v. in Ap horizons. (Table 4). In the 1 NPK plot, FC was greater than the 0NPK plot, but was not significantly different. FC clearly increased in 2NPK. Interestingly OMC was almost identical for both fertilization levels and so could not be the differentiating factor. Regardless of the fertilization level the Cd1 and Cd2 horizons showed FC values (23.37–29.44% v.), which were always less than those observed in the epipedons. In addition to FC, the key points that define water availability for plants are refill point – RP (pF 3.7) and wilting point – WP (pF 4.2). The coincidence of these points with the FC, best illustrates the total and readily available water. In the epipedons the TAW value (21.41–28.96% v.) was always greater than the corresponding value (14.32–20.80% v.) in the Cd1, and Cd2 horizons (Table 4). Along with the increase in fertilization dose, this indicator significantly increased in Ap, and remained at the same level in Cd1 and Cd2. Similar, though not as evident, dependencies were observed for RAW. The RAW:TAW ratio was almost identical, preferably high, in all experimental combinations (Table 4). The MH value which corresponds to humidity at pF 4.5 – was used to precisely determine the water retention curves. Its values which depended mainly on the content of the colloids, were similar and ranged from 2.70 to 2.85%. (Table 4).

Cluster dendrogram does not show clear trends (Fig. 2). On its basis, however, it can be cautiously concluded that the physical properties were similar in both fertilization combinations. There was also a clear alignment within the endopedons (Cd1, Cd2) (Fig. 2). Therefore, we conclude that additional NPK applications are superfluous.

Table 4
Soil water potentials of examined soils

Fertilization variant	Horizon	Depth (cm)	Moisture at pF (%v)					RAW (%v.)	TAW (%v.)	RAW:TAW
			2.0	2.2	3.7	4.2	4.5			
0 NPK	Ap	0–26+/–2	29.10bc	20.26bcd	13.50abc	7.69b	2.81bc	15.60bc	21.41c	0.73ab
	Cd1	26–67+/–3	27.00b	18.78b	11.77a	8.00bc	2.70a	15.23bc	19.00bc	0.80bc
	Cd2	67– 94+/–4	23.37a	16.10a	12.57ab	9.05cde	2.74ab	10.80a	14.32a	0.75ab
1 NPK	Ap	0–25+/–2	30.83c	21.57cde	13.59bc	6.30a	2.76abc	17.24c	24.53d	0.70a
	Cd1	25–73+/–4	29.44bc	22.32de	14.58c	8.64bcd	2.77abc	14.86bc	20.80bc	0.71ab
	Cd2	73–96+/–5	28.01b	18.37b	13.01abc	8.93cde	2.72ab	15.00bc	19.08bc	0.79abc
2 NPK	Ap	0–26+/–3	35.07d	22.66e	14.59c	6.11a	2.75ab	20.48d	28.96e	0.71ab
	Cd1	26–71+/–6	27.70b	26.29f	14.22bc	9.35de	2.85c	13.48ab	18.35b	0.73ab
	Cd2	71–97+/–5	29.33bc	19.50bc	12.66ab	10.05e	2.85c	16.67c	19.28bc	0.86c

α = 0.05/values marked with the same letters do not differ significantly

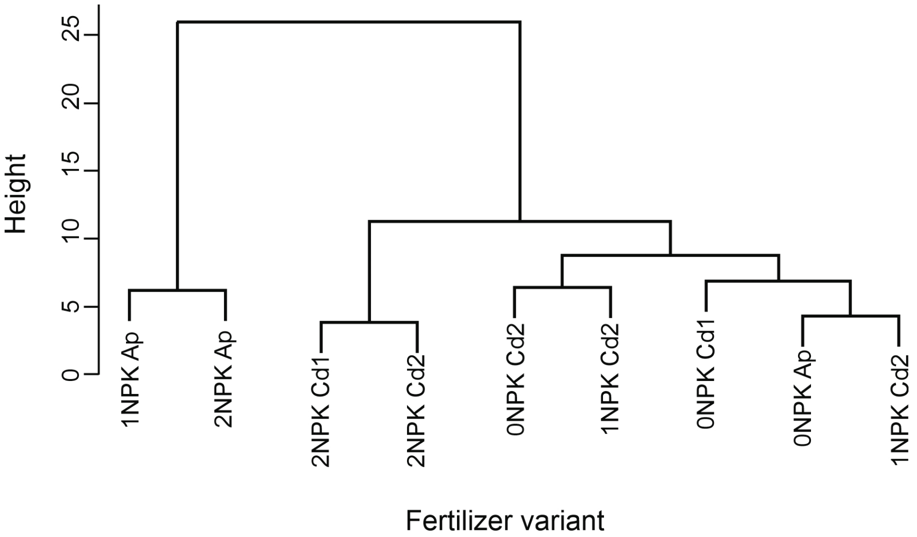

Fig. 2. Cluster analysis (Ward method with Manhattan distance) of similarities between genetic horizons in individual profiles

4. Discussion

After 42 years of reclamation, the tested Technosols should still be treated as very young soils (Leguédois et al., 2016; Otremba et al., 2020; Kozłowski et al., 2023). However, the distinguished genetic horizons in our study were well developed and clearly visible. The parent material exhibited characteristics typical of boulder loam formations from the Warta glaciation (Wojtasik, 1989; Spychalski et al., 2008; Czubla et al., 2013; Otremba et al., 2020). As a result of mining the overburden was mixed and partially homogenized – still remaining polydisperse. The result of this, the uniformity of the particle size distribution of all genetic horizons to the range of one texture subgroup. While BD values in fertilized epipedons that were systematically penetrated by grain roots, can be considered typical of mineral arable soils in the Central Polish Lowland, the BD value in the surface horizon in the 0 NPK plot was very high (Rząsa et al., 1999). Shrestha et al. (2009) also observed high density and high clay content values in post-mining areas in their study. Soil bulk density and total porosity differed significantly in all tested variants; these changes were favorable. Such a change is very eligible, because the high BD of epipedons is – from the agricultural point of view – difficult to accept, however, these values are still typical for central Polish boulder formations. Similar BD values in such deposits have been reported by Wojtasik (1989) and Rząsa et al. (1999); and higher values have been reported by Gilewska and Otremba (2018), Otremba et al. (2020) and Kozłowski et al. (2022). The effect of mineral fertilization on bulk density and porosity was also tested by Zhao et al. (2013) and Phares and Akaba (2022) who did note any improvement in these parameters. In contrast Chaduhary et al. (2017) observed a significant decrease in density and a significant increase in porosity as a result of many years of NPK fertilization. Moreover Naveed et al. (2014) reported a clear increase in porosity after NPK fertilization, also noted an increase in OMC and emphasize the linear relationship between these parameters. Literature contains reports on the beneficial effect of mineral fertilization on the organic carbon content in the top horizon of reclaimed soils (Gilewska and Otremba, 2001). This was confirmed by Abrar et al. (2020), who tested the effect of various forms of mineral and organic fertilization on soil properties. These authors noted a significant increase in the content of organic carbon in the top horizon of reclaimed soils after NPK fertilization. According to the research carried out by Gregorich et al. (1996), this is connected to an increase in root biomass in the topsoil. Other conclusions have been proposed by Adekiya et al. (2019), who suggested that the addition of NPK does not lead to an increase the C_{tot} content, because it does not directly supply organic matter. In contrast the decrease in the amount of organic carbon in the subsoil can be explained by the decrease in root biomass in this horizon (Shahbaz et. al., 2017). The above observations outlined above are in agreement with our findings here. In the tested soils, the increase in OMC was significant only in the Ap horizons and occurred in both fertilization plots. Interestingly, the OMC was almost identical in both fertilization plots – they did not differ significantly – which confirms previous observation that double fertilization is superfluous (Gilewska and Otremba, 2001). Most of the physical properties of Technosols fertilized with two doses of NPK were similar and at the same, time different from those observed in the unfertilized soil. The multi-year average yields also support the beneficial effect of applied NPK. The 0 NPK plot produced a low yield: 0.75 t ha^{-1} and yields were greater in both fertilized plots (1 NPK – 2.42 t ha^{-1}, 2 NPK – 2.79 t ha^{-1}, unpublished data). The similar pH values (7.53–7.71) across all tested soil material probably resulted from its partial homogenization during the dumping process. This was also confirmed by the slightly variable $CaCO_3$ content (6.54–8.83%, unpublished data). Similar results (6.96–7.81%) were obtained on such soils by Otremba et al. (2020). The lack of effect of mineral fertilization on pH was also noted by Zhao et al. (2013), while other authors have pointed to a statistically significant decrease in pH as a result of NPK fertilization (Tian et al., 2017).

In Ap horizons FC increased in tandem with increased NPK applications, and FC values were reduced but more consistent in endopedons, which suggest the influence of plants, both directly and indirectly. Similar conclusions were reached by Naveed et al. (2014), who noted favorable changes in the pF curve after fertilization with NPK although, the study by Bednik et al. (2020) did not show any effect. With very similar – appropriate – values of RP and WP, the retention capacity was shaped mainly by FC. Hence, the volatility of TAW and RAW was similar to FC. The RAW: TAW index, which generalizes the described water retention capacity and water availability for plants, was very even, and the values were similar to data characteristic of heavy mineral agricultural soils (Kaczmarek et al., 2021). The water properties observed for the surface horizons of Technosols tested here can be considered comparable to those reported for Ap horizons in mineral soils in Wielkopolska (Rząsa et al., 1999). The MH values, which can be roughly treated as moisture at pF=4.5, were very even and ranged from 2.70 to 2.85% v. In mineral soils, this characteristic depends mainly on the content of the clay fraction, which was almost identical across the tested samples. In the interpretation of the correlation of the examined properties, the most important were those concerning the content of organic matter – as a property whose improvement – in the authors' opinion – is one of the key conditions for successful reclamation. In this study OMC was positively and significantly correlated with TP and retention capacity, and negatively – with BD. At the same time, it should be emphasized that these relationships were not strong, which allows us to assume that another variable, which was not analyzed in this study, may be responsible for the favorable changes observed in the physical and water properties. We cautiously suggest that this could be microbial activity and physical penetration of the surface horizon by plant roots. Eynard (2001) observed a very clear relationship between root density and BD while Jassogne (2008) attributed particular importance to highly compacted soils. This author claimed that these pores can be used by young plants. The influence of plant roots on soil properties also includes their contribution to the supply of organic matter to the subsoil, which has been emphasized by e.g. Banfield et al. (2018).

All reports cited in the article include more or less extensive research testing the impact of agricultural technology on soil properties and the process of its reclamation. Often contradictory conclusions indicate the legitimacy of further search for optimal reclamation directions or optimal agrotechnics of already reclaimed soils. Equally important as this practical aspect is learning about the mechanisms taking place in the soil that lead to its reaction to the applied agricultural technology.

5. Conclusions

Mineral fertilization improved the physical and water properties in the surface horizons. However, the soil properties in the endopedons were much less favorable. Moreover, the beneficial effect of NPK fertilization on subsoil properties was not observed.

The most important and most favorable changes were an increase in total porosity and content of readily available water.

The NPK application resulted in a small but statistically significant increase in the content of organic matter in the soils.

Fertilization was effective with the single application of NPK fertilization. Additional applications appear superfluous.

The observed changes in soil characteristics were mostly advantageous for plant development, which could indicate that the reclamation approach implemented at this site was correct.

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Wpływ nawożenia NPK w rekultywacji rolnej na przekształcenia Technosoli na obszarze pogórniczym w rejonie Kopalni Węgla Brunatnego Konin

Słowa kluczowe

Nawożenie
Właściwości gleb
Tereny pogórnicze
Technosole

Streszczenie

W pracy oceniono wpływ wieloletniego, zróżnicowanego nawożenia NPK i monokultury zbożowej na właściwości fizyczne i wodne pogórniczych Technosoli. Badania przeprowadzono w 2022 r. na założonym w 1978 r. poletku doświadczalnym. Analizowane doświadczenie polowe założono na zwałowisku wewnętrznym odkrywki Pątnów Kopalni Węgla Brunatnego Konin. Na terenie badań od początku założenia doświadczenia do chwili obecnej uprawia się coroczny płodozmian zbożowy (żyto ozime naprzemiennie z pszenicą ozimą). Od 1988 r poletko doświadczalne podzielone jest na trzy warianty doświadczalne, na których zastosowano zróżnicowane nawożenie NPK. Teren badań stanowiły trzy poletka – w pracy oznaczone jako: 0 NPK, 1 NPK, 2 NPK. Na każdym z nich wykonano po trzy profile glebowe. Opisano ich budowę morfologiczną, a z poszczególnych poziomów genetycznych pobrano próbki o strukturze naruszonej i nienaruszonej (do cylindrów o objętości 100 cm^3). Wynik analiz zostały potraktowane jako powtórzenia i opracowane statystycznie. Pobrany materiał glebowy użyty został do wykonania analiz podstawowych właściwości fizycznych, wodnych i chemicznych gleb. Badane gleby zaliczono wg klasyfikacji WRB do grup gleb Spolic Technosols (Pantocalcaric, Katodensic, Pantoloamic, Ochric). Nawożenie mineralne powodowało poprawę właściwości fizycznych i wodnych w poziomach powierzchniowych. Zmian takich nie zaobserwowano w podpoziomach. Zastosowane nawożenie było skuteczne już dla dawki 1 NPK. Podwajanie jej wydaje się być nieuzasadnionym. Realizowany od ponad 45 lat model rekultywacji przyczynił się do poprawy warunków wzrostu roślin.