

The impact of fertiliser granules produced from waste on soil

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RECEIVED 24.02.2026

ACCEPTED 21.07.2026

AVAILABLE ONLINE 16.10.2026

Abstract: The growing volume of waste is driving research into its use as a nutrient source for plants. The study aimed to determine the effect of fertiliser granulates produced from waste on selected qualitative indicators of mineral soil following harvesting of test plants. To achieve this objective, fertiliser granulates produced from three types of waste were tested: industrial sewage sludge, ash and a mixture of sawdust from deciduous and coniferous trees.

Increasing fertiliser granulates doses increased pH_{KCl} in the soil after harvesting both test plants. Significant differences in pH_{KCl} in the soil were observed between the first and third doses. The doses of granulates A, B, C, and D applied to the soil after harvesting both test plants increased N, P, K, Ca, Mg, and S levels compared to the control. The total Ca and Mg content in the soil after the application of granulates A and C was, on average, 17.8% and 17.5% higher than in the cases where granulates B and D were applied. It was shown that under the influence of the tested granulates A, B, C, and D the total of Cu, Zn, Cr, and Cd in the soil after harvesting the test plants increased slightly. The application of fertiliser granulates to the soil caused a slight increase in their content. The heavy metal Cd, Cr, Cu and Zn content indicates that the soil did not contain excessive amounts of these metals before and after the experiment.

Keywords: available forms, correlations, fertilisation, granulates from waste, heavy metals, macronutrients total, soil

INTRODUCTION

Fertilisation with fertilisers containing organic matter has a decisive impact on soil fertility and fertilisation. Many negative changes have been observed in the fertiliser economy in Poland in recent years. These relate to low NPK consumption in the 2023/2024 marketing year, which amounted to $122 \text{ kg} \cdot \text{ha}^{-1}$, which was 8.20% lower compared to the 2019/2020 season. The reason is the increase in mineral fertiliser prices and the introduction of new fertilisers and changes in their product range. Further negative changes are related to the reduction in the number of farm animals, which results in lower production and application of natural fertilisers (Krzywy *et al.*, 2012; Bech, 2014). Changes in crop sowing patterns and a lack of crop rotation (frequent cultivation of the same crop in a given field). The area of cultivation of cereals and industrial plants has increased, which leads to a negative balance of organic matter and nutrients in soils and a reduction or complete abandonment of the use of lime fertilisers, causing high soil acidification. As Skowrońska (2007) points out, such practices can lead to reduced fertility and yield. The European Green Deal was published based on reports of

negative climate change and the deteriorating environmental condition in the European Union. The Green Deal aims to reduce the negative impact of agriculture on the environment (Communication, 2020).

It is advisable to limit the application of mineral and natural fertilisers and plant protection products, which translates into a reduction in the introduction of nutrients into the soil. Wierzbowska *et al.* (2016), nutrients contained in waste can be returned to the soil in the form of fertiliser, and their proper use will reduce the application of mineral fertilisers. However, the use of mineral fertilisers in excessive doses can cause soil contamination. They can also be a source of heavy metals. A consequence of the aforementioned changes is the testing of various raw materials, products, and wastes that can be a source of organic matter and nutrients for plants.

The powerful and rapid development of technologies used to produce innovative goods for humans has contributed to the generation of large amounts of waste (Łabętowicz, Stępień and Kobiś, 2019). Sewage sludge management includes a complete ban on landfilling and aims to increase the amount of sludge processed or thermally transformed (Callegari and Capodaglio,

2018). Thermal disposal is expensive, so the waste must be used in another way, e.g. processed. Kacprzak *et al.* (2017) states that sewage sludge, which is waste, should be used to obtain as many nutrients as possible by producing fertilisers or composts, while maintaining sanitary and chemical safety requirements.

Therefore, research has been initiated on the possibility of using waste for fertilisation purposes, which has a positive impact on soil fertility parameters and the quality of crops without negative impact on the environment (Basu *et al.*, 2009).

For many years, the reserves of phosphate rock and apatite, necessary for the production of mineral phosphate fertilisers, have been dwindling (Daneshgar *et al.*, 2018). Obtaining macronutrients, including P and N, from sewage sludge is an important element for the economy (Huygens and Saveyn, 2018; Lipińska, 2018). After processing properly selected waste, fertilisers, organic and organic-mineral mixtures and composts will be produced (Pawelec *et al.*, 2021). Processing waste with fertiliser value must be environmentally safe. Kirchmann *et al.* (2017) indicates that the impact of soil treatments using wastes applied individually, together in mixtures or granulated fertilisers on the circulation of macronutrients in the soil-plant system should be assessed.

The aim of the vegetation study was to determine the effect of fertiliser granulates produced from waste on the total content and available forms of macronutrients and selected heavy metals in the soil after harvesting the test plants. To achieve the research objective, fertiliser granulates produced from three types of waste were tested: industrial sewage sludge, ash and a mixture of sawdust from deciduous and coniferous trees. Mineral fertilisers ammonium phosphate (18% N and 46% P₂O₅) and potassium salt (60% K₂O) were added to the granulates to supplement the basic nutrients. The four produced granulates A, B, C and D were used in three doses. The test plants were spring rapeseed ('Larisa' variety) and spring triticale ('Milikaro' variety).

MATERIAL AND METHODS

RESEARCH METHODOLOGY

The precise chemical properties of the waste allowed the development of recipes for the material composition of fertiliser granulates. Industrial sewage sludge is generated as waste from the wastewater treatment plant at Grupa Azoty "Police" (Pol.: Grupa Azoty Zakłady Chemiczne „Police” S.A.) Tests showed that the industrial sludge used did not contain *Salmonella* bacteria or live gastrointestinal parasite eggs. Ash came from the Adamów S.A. power plant and sawdust from deciduous and coniferous trees from a sawmill. To achieve the correct N:P:K ratio, ammonium phosphate and potassium salt were added to the granules as a source of N, P, and K. The resulting organic-mineral granulates were used in pot-growing experiments. The test plants were spring rapeseed ('Larisa' variety) and spring triticale ('Milikaro' variety). The vegetation-pot experiment was carried out in Poland in the vegetation hall belonging to the West Pomeranian University of Technology in Szczecin in a year 2021.

Soil from the Ap horizon of the production field of the Agricultural Experimental Station in Lipnik near Stargard (Pol.: Rolnicza Stacja Doświadczalna w Lipniku) was used for vegetation studies. Soil with a textural class of the sandy loam (SL), type Endocalcaric Cambisols (FAO, 2015), was used for the experi-

ment. It is a light soil with a slightly acidic reaction (pH_{KCl} 6.0). It was characterised by a narrow C:N ratio and low organic carbon and organic matter content. Chemical analysis of the soil showed that it contained 0.86 N, 1.50 P, 2.57 K, 2.11 Ca, 0.56 Mg, and 1.25 S in g·kg⁻¹ DM. The content of plant-available forms of P (60.9 mg·kg⁻¹ DM), K (121 mg·kg⁻¹ DM) and Mg (42.5 mg·kg⁻¹ DM) indicated a medium abundance. The granulates were produced using industrial sewage sludge and ash, so the total and soluble content of certain heavy metals in the soil was additionally determined.

The total and soluble content of the heavy metals Cd, Cu, Cr, and Zn tested in the soil did not exceed the standards for plant cultivation and land reclamation specified in the Regulation of the Minister of Climate and Environment (Rozporządzenie, 2024). The complete chemical analysis of the soil before the experiment was tabulated and published in Moździerz, Jałoszyński and Jarnuszewski (2020), Moździerz (2022), Moździerz and Gamrat (2023).

The experimental design is presented in Table 1. It takes into account two factors. The first factor is fertiliser granulates A, B, C, D. The second factor is increasing doses of fertiliser granulates – I, II, III. The two-factor experiment was conducted in a randomised block design. Each fertiliser variant was performed in four replicates (12 fertiliser variants × 4 replicates = 48 experimental objects + control).

Table 1. Experimental design

Type of granulate	Granulate doses		
	I single	II double	III triple
A	+	+	+
B	+	+	+
C	+	+	+
D	+	+	+
Control	–	–	–

Explanations: I = 0.24 g N per pot (80 kg N·ha⁻¹), II = 0.48 g N per pot (160 kg N·ha⁻¹), III = 0.72 g N per pot (240 kg N·ha⁻¹); A = 30% industrial sewage sludge, 30% ash, 10% sawdust, 15% ammonium phosphate, 15% KCl, B = 40% industrial sewage sludge, 20% ash, 10% sawdust, 15% ammonium phosphate, 15% KCl, C = 20% industrial sewage sludge, 40% ash, 10% sawdust, 15% ammonium phosphate, 15% KCl; D = 50% industrial sewage sludge, 20% ash, 10% sawdust, 10% ammonium phosphate, 10% KCl.

Source: own elaboration.

The soil to be tested was sieved to remove contaminants. They were then weighed at 9 kg each and placed in experimental pots. The doses of the tested granulates were determined based on their N content.

In spring, the calculated doses of granulates were introduced into pots with mineral soil and mixed to a depth of 5 cm. Spring rapeseed seeds of the 'Larissa' variety and spring triticale grain of the 'Milikaro' variety were sown in the amount of 20 pieces each seed material. The pots with the test plants were watered with distilled water, maintaining soil moisture at 60% of full water capacity throughout the experiment. Once the rapeseed and triticale had reached a height of 10 cm, a selection was made, leaving 5 plants in each pot. Nitrogen fertiliser was applied as top dressing in the form of urea (46% N). It was applied in an

aqueous solution. The N dose was 92 kg per ha ($200 \text{ kg} \cdot \text{ha}^{-1}$ of urea). Calculated per 1 pot, this was a value of 0.276 g of N.

The material composition of granulates, the concentration of nutrients in them and the content of macro- and micronutrients in rapeseed and triticale grain were partially published in the work by Możdżer, Jałoszyński and Jarnuszewski (2020) and Możdżer and Gamrat (2023).

ANALYTICAL METHODS

The following parameters were determined in the soil samples taken before and after the experiment: dry mass by the drying method according to PN-ISO 11465 (Polski Komitet Normalizacyjny, 1999); pH potentiometrically in $1 \text{ mol} \cdot \text{dm}^{-3}$ KCl according to PN-ISO 10390 (Polski Komitet Normalizacyjny, 1997); N, organic carbon and S were determined using a Vario Max CNS elemental analyser; total P was determined using the Barton colorimetric method after prior mineralisation of the samples in a mixture of nitric acid(V) and perchloric acid(VII) in a 1:1 ratio on a Lambda 150 spectrophotometer from Perkin Elmer, total K and Ca – by flame photometry, total Mg, Cd, Cu, Mn, Ni, Pb and Zn by ASA atomic absorption spectrometry on a Perkin Elmer AAS 300 spectrometer (Jones and Case, 1990). The basic solution for determining the total content of macronutrients and heavy metals was obtained after wet mineralisation of the soil material according to the Polish standards PN-ISO 11466 (Polski Komitet Normalizacyjny, 2001) and PN-ISO 11047 (Polski Komitet Normalizacyjny, 2001). Available P and K according to PN-R-04022 (Polski Komitet Normalizacyjny, 1996) and available forms of Mg, according to PN-R-04023 (Polski Komitet Normalizacyjny, 1996). The average soil pH values from individual experimental sites were calculated by converting pH_{KCl} to hydrogen-ion concentration. The content of macronutrients and heavy metals in the soil after rapeseed and triticale harvest was determined for each fertiliser variant in three replicates.

The statistical analysis of the test results was performed using a two-factor analysis of variance in a randomised block design using the Statistica 13.3 programme. To determine the

significance of the differences, half-confidence intervals were used with Tukey's test at the 0.05 level. Pearson's linear correlation coefficient (r) was calculated for the total content and the bioavailable forms of P, K, and Mg in the soil at the end of the experiment. The significance of the correlation coefficient was tested using the Student's t -test.

RESULTS AND DISCUSSION

The pH_{KCl} value in the mineral soil at the control site after the harvest of rapeseed and spring triticale was 5.90 and 5.80, respectively 0.1 and 0.2 units reduced it compared to the value before the experiment (Tab. 2).

After harvesting spring rapeseed, the pH_{KCl} value of the soil on the plots where fertiliser granulate A (30% industrial sewage sludge and 30% ash) and C (20% industrial sewage sludge and 40% ash) were applied was higher by 0.4 and 0.6 units, respectively, compared to the control. The same relationship occurred in the soil after the spring triticale harvest. These values were 0.4 and 0.5 units higher than in the control. The pH_{KCl} in the soil after harvesting rapeseed and spring triticale on plots with granulates A and C applied was significantly higher compared to plots where granules B with 40% industrial sewage sludge and 20% ash and granules D with 50% industrial sewage sludge and 20% ash were applied. Increasing fertiliser granule doses increased the pH_{KCl} in the soil after harvesting both test crops. Significant differences in the pH_{KCl} value in the soil were found between the first and third doses. Based on the results, it can be concluded that the higher the lignite ash content in the soil, the higher the pH_{KCl} . Similar results of studies on the effect of brown coal ash on the pH_{KCl} of light soil were confirmed (Antonkiewicz *et al.*, 2020).

The studies showed that after the spring rapeseed harvest, there was 1.35% more organic carbon and 1.84% more organic matter in the soil than after the spring triticale harvest. On the other hand, the total content of N, P, K, Mg, Ca and S was higher in the soil after the spring triticale harvest by 8.23, 10.00, 9.77, 1.32, 3.44 and 7.95% respectively, in the soil after spring triticale harvest compared to the soil after rapeseed harvest (Tab. 3).

Table 2. The influence of tested granulates A, B, C and D on the pH_{KCl} value in the soil after harvesting the test plants

Granulate (g)	pH _{KCl}							
	rape				triticale			
	dose of granule (d)							
	I	II	III	mean	I	II	III	mean
A	6.20	6.30	6.40	6.30	6.10	6.20	6.40	6.20
B	5.90	6.00	6.00	6.00	5.80	5.90	6.00	5.90
C	6.30	6.50	6.60	6.50	6.20	6.30	6.40	6.30
D	6.00	6.00	6.00	6.00	5.90	6.00	6.00	6.00
Mean	6.10	6.20	6.25	6.18	6.00	6.10	6.20	6.10
Control	5.90				5.80			
Output value	6.00							
LSD _{0.05}	g = 0.192, d = 0.149, g × d = n.s.				g = 0.170, d = 0.131, g × d = n.s.			

Explanations: LSD = least significant difference, n.s. = non significant; I, II, III, A, B, C, D as in Tab. 1.

Source: own study.

Table 3. The effect of tested granulates A, B, C and D on the content of organic matter, organic carbon, N and P in the soil after harvesting the test plants

Granulate (g)	Rape				Triticale			
	dose of granule (d)							
	I	II	III	mean	I	II	III	mean
Organic matter (%)								
A	1.64	1.65	1.66	1.65	1.62	1.64	1.65	1.63
B	1.67	1.68	1.69	1.68	1.64	1.65	1.66	1.65
C	1.61	1.62	1.62	1.61	1.57	1.60	1.62	1.59
D	1.67	1.68	1.69	1.68	1.62	1.64	1.65	1.63
Mean	1.65	1.66	1.67	1.66	1.62	1.63	1.65	1.63
Control	1.59				1.52			
Output value	1.60							
LSD _{0.05}	g = 0.017, d = 0.013, g × d = n.s.				g = 0.018, d = 0.015, g × d = n.s.			
Organic carbon (g·kg ⁻¹ DM)								
A	9.64	9.73	9.79	9.72	9.51	9.61	9.71	9.61
B	9.85	9.84	9.91	9.87	9.65	9.69	9.76	9.70
C	9.47	9.51	9.53	9.50	9.29	9.41	9.48	9.39
D	9.83	9.90	9.95	9.89	9.69	9.79	9.88	9.79
Mean	9.70	9.74	9.80	9.75	9.53	9.63	9.71	9.62
Control	9.50				9.33			
Output value	9.63							
LSD _{0.05}	g = 0.07, d = 0.06, g × d = n.s.				g = 0.06, d = 0.04, g × d = n.s.			
N (g·kg ⁻¹ DM)								
A	0.84	0.86	0.89	0.86	0.87	0.95	0.98	0.93
B	0.84	0.85	0.90	0.86	0.86	0.98	1.00	0.95
C	0.84	0.88	0.89	0.87	0.88	0.94	1.00	0.94
D	0.81	0.81	0.83	0.82	0.83	0.96	0.91	0.87
Mean	0.83	0.85	0.88	0.85	0.86	0.93	0.97	0.92
Control	0.79				0.85			
Output value	0.83							
LSD _{0.05}	g = n.s, d = 0.04, g × d = n.s.				g = 0.058, d = 0.045, g × d = n.s.			
P (g·kg ⁻¹ DM)								
A	1.49	1.53	1.58	1.53	1.62	1.69	1.74	1.68
B	1.47	1.52	1.59	1.53	1.60	1.69	1.76	1.68
C	1.49	1.53	1.60	1.54	1.62	1.71	1.76	1.70
D	1.37	1.47	1.45	1.41	1.47	1.52	1.61	1.53
Mean	1.45	1.50	1.55	1.50	1.58	1.65	1.72	1.65
Control	1.37				1.46			
Output value	1.50							
LSD _{0.05}	g = 0.037, d = 0.029, g × d = n.s.				g = 0.012, d = 0.009, g × d = 0.02			

Explanations as in Tabs. 1 and 2.

Source: own study.

The soil after harvesting test plants on sites where granulates B and D were used contained the most organic carbon and organic matter. Granulate C contributed to the smallest increase in organic carbon content, by 4.00 and 3.78%, respectively, and organic matter, by 4.35 and 3.14%, respectively, in the tested soil compared to granulates B and D (Tab. 3). The organic carbon and organic matter content in the soil after harvesting both test plants on sites where granulates B and D were applied was significantly higher than that with granulate C. The results indicate that a higher proportion of sewage sludge in fertiliser granulates (B and D) increased the organic carbon content and had a beneficial effect on the decomposition of organic matter in the soil. An increase in organic carbon content in light soil after the application of sewage sludge or compost produced with its participation was reported (Kalembasa, Godlewska and Wysockiński, 2008). Antonkiewicz *et al.* (2020) report that the organic carbon content in the soil increased after the application of sewage sludge and ash $10.2 \text{ g}\cdot\text{kg}^{-1} \text{ DM}$. Similar results were obtained in the experiment. The differences in the effects of individual doses of fertiliser granulates on soil organic carbon and organic matter content were not always significant.

The applied doses of fertiliser granulates in the tested soil after rapeseed harvest increased the content of total N, P, K, Ca, Mg and S in relation to the control by 7.59, 9.48, 17.20, 17.70, 11.50 and 9.83%, respectively (Tabs. 3 and 4). Similar results were reported by Antonkiewicz *et al.* (2020) who found increases in soil N, K, Ca, and Mg content under the influence of sewage sludge and ash. The soil contained significantly more total Ca and

Mg after harvesting both plants on sites where fertiliser granulates A and C were applied, compared to sites where granulates B and D were applied. The total Ca and Mg content in the soil after the application of granulates A and C was, on average, 17.8 and 17.5% higher, respectively, than at sites where granulates B and D were applied (Tab. 4). It was related to the high total Ca and Mg content of ash. This thesis is supported by research conducted by Gibczyńska *et al.* (2009) who showed that ash contains significant amounts of Ca and Mg, which also alter soil pH_{KCl} . The soil contained the least total P and K after harvesting both test plants on the site where granulate D were applied. The highest P and K content in the soil was observed after applying granulates C with the share of 20% of industrial sewage sludge and 40% ash compared with granulate D the share of 50% of industrial sewage sludge and 40% ash (Tabs. 3 and 4).

The total P and K content in the soil under the influence of granulate D was significantly lower than at sites where fertiliser granulates A, B and C were applied. The tested granulates A, B, and C had no significant effect, as they did not cause differences in total phosphorus and K content in the tested soil after harvesting both test plants.

The applied granulates A, B, C, and D, produced from industrial sewage sludge and ash, are rich in phosphorus; therefore, their application increases the soil's phosphorus content. Similar results were obtained by Jama-Rodzeńska and Galka (2022), Czekała (2008). The possibility of total phosphorus accumulation in the soil should also be considered. This phenomenon is caused by the high Ca and Mg content in ash,

Table 4. The effect of tested granulates A, B, C and D on the content of K, Mg, Ca and S in the soil after harvesting the test plants

Granulate (g)	Rape				Triticale			
	dose of granule (<i>d</i>)							
	I	II	III	mean	I	II	III	mean
K (g·kg ⁻¹ DM)								
A	2.24	2.31	2.40	2.31	2.48	2.54	2.62	2.55
B	2.27	2.36	2.40	2.34	2.50	2.52	2.61	2.54
C	2.28	2.33	2.48	2.36	2.50	2.54	2.60	2.55
D	1.93	1.98	2.10	2.00	2.18	2.23	2.36	2.25
Mean	2.18	2.24	2.34	2.25	2.41	2.46	2.55	2.47
Control	1.92				1.97			
Output value	2.37							
LSD _{0.05}	g = 0.038, d = 0.03, g × d = n.s.				g = 0.043, d = 0.34, g × d = n.s.			
Mg (g·kg ⁻¹ DM)								
A	0.56	0.62	0.61	0.61	0.58	0.65	0.69	0.64
B	0.51	0.54	0.57	0.54	0.51	0.53	0.55	0.53
C	0.61	0.63	0.66	0.63	0.63	0.67	0.72	0.67
D	0.52	0.54	0.55	0.54	0.53	0.56	0.59	0.56
Mean	0.56	0.58	0.60	0.58	0.56	0.60	0.64	0.60
Control	0.52				0.48			
Output value	0.56							
LSD _{0.05}	g = 0.019, d = 0.015, g × d = n.s.				g = 0.04, d = 0.03, g × d = n.s.			

cont. Tab. 4

Granulate (g)	Rape				Triticale			
	dose of granule (d)							
	I	II	III	mean	I	II	III	mean
Ca (g·kg ⁻¹ DM)								
A	2.23	2.33	2.43	2.33	2.28	2.33	2.41	2.34
B	1.97	2.15	2.14	2.09	2.03	2.07	2.18	2.09
C	2.45	2.55	2.69	2.56	2.51	2.61	2.69	2.60
D	1.91	2.08	2.18	2.05	2.05	2.11	2.18	2.11
Mean	2.14	2.28	2.36	2.26	2.22	2.28	2.36	2.29
Control	1.92				2.01			
Output value	2.11							
LSD _{0.05}	g = 0.06, d = 0.05, g × d = n.s.				g = 0.06, d = 0.04, g × d = n.s.			
S (g·kg ⁻¹ DM)								
A	1.26	1.32	1.35	1.31	1.38	1.50	1.55	1.47
B	1.29	1.33	1.36	1.33	1.40	1.49	1.53	1.47
C	1.36	1.36	1.39	1.37	1.41	1.52	1.57	1.50
D	1.32	1.35	1.38	1.35	1.34	1.41	1.46	1.40
Mean	1.31	1.34	1.37	1.34	1.38	1.48	1.53	1.46
Control	1.22				1.19			
Output value	1.25							
LSD _{0.05}	g = n.s, d = 0.05, g × d = n.s.				g = 0.07, d = 0.05, g × d = n.s.			

Explanations as in Tabs. 1 and 2.

Source: own study.

which contributes to the formation of poorly soluble P compounds Smol, Kulczycka and Kowalski (2016), Jama-Rodzeńska, Sowiński and Kozieł (2021).

The most significant increase in S content after rape-seed harvest was observed between the first and third doses of granulate A, amounting to 7.14%. Granulate B caused an increase in N and P content between the first and third doses by 7.14 and 8.16% (Tabs. 3, 4). Granulate C had the most remarkable impact on soil Mg content between the first and third doses. The increase was 8.20%. Granulate D, on the other hand, caused an increase in K content by 8.80% and Ca content by 14.1% between the first and third doses. It was also found that granulate D increased P concentration between the first and second doses by 7.29%.

The increasing doses of granulates A, B, C and D applied to the soil after the spring triticale harvest contributed to an increase in N, P, K, Ca, Mg and S compared to the control by 8.23, 13.0, 13.3, 13.9, 25.0 and 22.6%, respectively. The most significant increase in soil Mg content (18.9%) and S content (12.3%) was obtained between the first and third doses of granulate A. Granulate B caused an increase in N, P and Ca content between the first and third doses by 16.3, 10.0 and 7.38%, respectively. The increase in N content under the influence of fertilising light soil with, among other things, industrial sewage sludge is indicated by research Czekala (2008), Antonkiewicz (2012), Łabętowicz *et al.* (2019). Granulate D had the most considerable impact on soil K content between the first and third doses. The increase was

8.25%. It was found that granulate D contributed to a 15.7% increase in N content between the first and second doses. The differences in macronutrient content in the soil after harvesting both test plants were not always significant.

The soil contained more macronutrients after harvesting the test plants compared to the control. It was due to the movement of macronutrients from the test plants at the end of the growing season, from the roots to the soil.

Czekala (2004) states that the impact of introducing Ca and S into the soil deserves special attention, as these are deficient components in Polish soils. The application of granulates A and C increased the total Ca, S, and Mg content in the soil after harvesting both test plants. This is the result of adding 30 and 40% of ash, the primary source of these elements, together with granulates A and C, respectively. The results obtained regarding the Ca and Mg content of ash are confirmed by the studies. Antonkiewicz *et al.* (2018) on the other hand, reports that the increase in macronutrient content in light soil after the harvest of test plants was due to the application of industrial sewage sludge. The total N, P, K, Ca, Mg and S content in the soil at the end of the experiment was largely dependent on the type of granulates and their nutrient content.

Significantly, the soil to which fertiliser granulate D containing 50% industrial sewage sludge and 20% ash and the least mineral fertilisers were added, contained the least amount of absorbable P, K and Mg after the experiment compared to

fertiliser granulates A, B and C (Tab. 5). It is related to the lowest concentration of nutrients in granulate D. A significant increase in available P content after the rapeseed harvest was observed between the first and third doses of granulate A, amounting to 9.05%. The application of granulate B increased K and Mg content by 17.40 and 7.26%, respectively, between the first and third doses. The study showed that granulate A caused a slight increase in available Mg content of 0.70% in the soil between the second and third doses. On the other hand, granulates C and D applied increased available P in the soil between the first and third doses. The differences in the content of macronutrients in the soil after rapeseed harvest were not always significant.

The most remarkable increase in the content of available P by 8.14%, K by 15.3% and Mg by 6.45% after triticale harvest was obtained between the first and third doses of granulate B.

Granulates A and D had the same effect on the increase in K content by 13.7% between the first and third doses. Granulate D was shown to contribute to a slight increase in available Mg content of 0.96% in the soil between the second and third doses. Increasing doses of fertiliser granulates generally increased the soil content of available P, K and Mg after triticale harvest. The differences in effect between the first, second, and third doses were not always significant.

The K content after harvesting both test plants, under the influence of the application of granulates A, B, C, and D, indicates that the soil has a high K content, whereas before the experiment, it was classified as having a medium content. The exception is the first dose of granulate D. No such relationship was found in the content of absorbable forms of P and Mg in the tested soil fertilised with the tested granulates. However, the content of the

Table 5. The effect of tested granulates A, B, C and D on the content of available P, K and Mg in the soil after harvesting the test plants

Granulate (g)	Rape				Triticale			
	dose of granule (<i>d</i>)							
	I	II	III	mean	I	II	III	mean
Available P (mg·kg ⁻¹ DM)								
A	63.0	65.7	68.7	65.8	62.5	63.9	67.4	64.6
B	63.6	66.9	67.8	66.1	62.6	65.8	67.7	65.4
C	63.8	65.8	67.5	65.7	63.1	65.9	67.5	65.5
D	61.4	63.2	65.0	63.0	59.9	62.3	63.6	62.0
Mean	62.9	65.4	67.2	65.2	62.0	64.5	66.6	64.4
Control	59.3				58.3			
Output value	60.9							
<i>LSD</i> _{0,05}	<i>g</i> = 1.51, <i>d</i> = 1.17, <i>g</i> × <i>d</i> = n.s.				<i>g</i> = 0.84, <i>d</i> = 0.65, <i>g</i> × <i>d</i> = n.s.			
Available K (mg·kg ⁻¹ DM)								
A	126	140	146	137	131	138	149	139
B	126	143	148	139	131	137	151	140
C	126	142	145	138	138	141	151	143
D	121	126	132	126	124	130	141	132
Mean	125	138	143	135	131	137	148	138
Control	117				117			
Output value	121							
<i>LSD</i> _{0,05}	<i>g</i> = 9.56, <i>d</i> = 7.43, <i>g</i> × <i>d</i> = n.s.				<i>g</i> = 4.17, <i>d</i> = 3.24, <i>g</i> × <i>d</i> = n.s.			
Available Mg (mg·kg ⁻¹ DM)								
A	42.6	42.4	42.7	42.5	41.9	42.5	43.1	42.5
B	39.9	41.2	42.8	41.3	40.3	41.9	42.9	41.7
C	43.5	44.9	45.7	44.7	43.6	42.8	44.8	43.7
D	40.8	41.9	42.9	41.7	41.4	41.6	41.8	41.5
Mean	41.7	42.6	43.4	42.6	41.7	42.2	43.1	42.4
Control	39.9				39.3			
Output value	42.5							
<i>LSD</i> _{0,05}	<i>g</i> = 1.53, <i>d</i> = 1.19, <i>g</i> × <i>d</i> = n.s.				<i>g</i> = 1.28, <i>d</i> = 0.99, <i>g</i> × <i>d</i> = n.s.			

Explanations as in Tabs. 1 and 2.

Source: own study.

assimilable form of P allowed the soil to be classified as having a high P content only on sites where the third dose of granulates A, B, C, and D was applied.

The applied fertiliser granulates A, B, C and D increased the content of absorbable forms of P, K and Mg in the tested soil compared to the control and the initial value.

The effects of granulates A, B, C, and D on increasing the content of plant-available forms of P and K in soil after harvesting both test plants were beneficial, in light of reports of increasingly frequent deficiencies of these components in Polish soils (Lipiński, 2019; Tkaczyk and Rutkowska, 2020).

According the Institute of Soil Science and Plant Cultivation in Puławy (Pol.: Instytut Uprawy i Nawożenia Gleby – PIB) states that in the topsoil layer (0–20 cm) of light soils, the natural content of heavy metals should not exceed for Cd – 0.50, for Cu – 25.0 and for Zn – 70.0 mg·kg⁻¹ DM. The results, presented in Table 6, indicate that the soil did not contain excessive concentrations of heavy metals before or after the experiment. The fertiliser granulates introduced into the soil did not cause the total heavy metal content to exceed the standards. The total content of Cd, Cu and Cr in the control soil after harvesting both test plants did not differ significantly from the results obtained before the experiment (Tab. 6). The average total contents of Cd, Cu, Cr, and Zn in the soil after harvesting both test plants did not differ significantly. After harvesting rapeseed and triticale, the soil contained the highest total Cd, Cu, Cr and Zn after application of granulate D. The soil contained the lowest total Cd after application of granulate C. Significantly less Cu, Cr and Zn was

found in the soil from sites where granulates A, B and C compared to granulate D. Increasing doses of fertiliser granulates in the tested soil after rapeseed harvest increased the total Cu, Zn, Cd and Cr content by 2.90, 4.94, 47.6 and 1.14%, respectively, compared to the control. A similar relationship was found in the soil after triticale harvest. The most significant increase in the content of the heavy metals discussed after rapeseed and triticale harvest in the soil was found between the first and third doses of the tested fertiliser granulates. Granulates A and C increased the Cd content between the first and third doses by 26.9 and 20.8%, respectively. Granulate D, on the other hand, caused a 12.1% increase in the Cd content in the soil. The tests showed that granulate B had the least impact on soil Cd content. The soil Zn content was 3.51% higher as a result of the application of granulate D between the first and third doses. An increase in the Zn content in the soil of 4.70% was found at the same level under the influence of the application of granulates A and C after the triticale harvest between the first and third doses. The studies showed that after harvesting both test plants, the increase in Cu and Cr content in the soil following the application of granulates A, B, C, and D between the first and third doses was slight, ranging from 0.5 to 2.4%. It was found that a 50% share of industrial sewage sludge in granulate D increased the soil concentration of heavy metals after harvesting both test plants. This thesis is confirmed by studies which showed an increase in the total content of certain heavy metals in light soil after the application of industrial sewage sludge (Baran, Wójcikowska-Kapusta and Żukowska, 2008; Pogrzeba, Rusinow-

Table 6. The effect of tested granulates A, B, C and D on the total content of Cu, Zn, Cd and Cr in the soil after harvesting the test plants

Granulate (g)	Rape				Triticale			
	dose of granule (d)							
	I	II	III	mean	I	II	III	mean
Cu (mg·kg ⁻¹ DM)								
A	8.69	8.80	8.85	8.78	8.79	8.87	8.89	8.85
B	8.76	8.87	8.97	8.87	8.81	8.86	8.93	8.87
C	8.78	8.87	8.91	8.85	8.76	8.83	8.90	8.83
D	8.89	9.00	9.04	8.98	8.95	8.95	9.00	8.97
Mean	8.78	8.89	8.94	8.87	8.83	8.88	8.93	8.88
Control	8.62				8.78			
Output value	8.60							
LSD _{0.05}	g = 0.07, d = 0.06, g × d = n.s.				g = 0.08, d = 0.06, g × d = n.s.			
Zn (mg·kg ⁻¹ DM)								
A	35.2	35.9	36.2	35.8	36.1	36.5	37.8	36.8
B	35.8	35.9	35.8	35.8	37.0	37.1	38.3	37.5
C	34.5	35.3	35.4	35.4	36.2	36.9	37.9	37.0
D	37.0	37.7	38.3	37.6	36.8	37.4	38.7	37.6
Mean	35.6	36.2	36.4	36.1	36.5	37.0	38.2	37.2
Control	34.4				35.2			
Output value	35.7							
LSD _{0.05}	g = 0.06, d = 0.05, g × d = n.s.				g = 0.49, d = 0.38, g × d = n.s.			

cont Tab. 6

Granulate (g)	Rape				Triticale			
	dose of granule (d)							
	I	II	III	mean	I	II	III	mean
Cd (mg·kg ⁻¹ DM)								
A	0.26	0.30	0.33	0.30	0.26	0.27	0.29	0.28
B	0.32	0.33	0.35	0.33	0.29	0.30	0.32	0.30
C	0.24	0.26	0.29	0.26	0.24	0.25	0.29	0.26
D	0.33	0.36	0.37	0.35	0.30	0.35	0.36	0.34
Mean	0.29	0.31	0.34	0.31	0.27	0.29	0.31	0.29
Control	0.21				0.20			
Output value	0.22							
LSD _{0.05}	g = 0.03, d = 0.02, g × d = n.s.				g = 0.03, d = 0.03, g × d = n.s.			
Cr (mg·kg ⁻¹ DM)								
A	8.74	8.82	8.85	8.80	8.79	8.94	8.93	8.89
B	8.72	8.83	8.84	8.80	8.77	8.85	8.95	8.86
C	8.75	8.80	8.83	8.80	8.77	8.87	8.94	8.86
D	8.89	8.97	8.98	8.95	8.87	8.96	9.01	8.95
Mean	8.76	8.86	8.88	8.84	8.80	8.91	8.96	8.89
Control	8.74				8.72			
Output value	8.80							
LSD _{0.05}	g = 0.06, d = 0.04, g × d = n.s.				g = 0.08, d = 0.06, g × d = n.s.			

Explanations as in Tabs. 1 and 2.

Source: own study.

ski and Krzyżak, 2018). Studies by other authors conducted on light soils fertilised with ash indicate increases in the content of Cd, Cu, and Pb, and a decrease in Zn (Kabata-Pendias 2004). Antonkiewicz (2007; 2009) reports that on light soil fertilised with increasing doses of ash, there was a systematic increase in the content of Cu and Zn, and a decrease in the content of Cd.

The limits of the total content of Cd, Cu and Zn soil after the completion of the tests, in accordance with the standards specified by the Institute of Soil Science and Plant Cultivation in Puławy, are classified as group “a” and pollution level “0” (Maliszewska-Kordybach, Smreczak and Klimkowicz-Pawlas, 2013). Therefore, it can be concluded that the applied granulates A, B, C, and D, containing industrial sewage sludge and ash, did not cause heavy metals soil contamination. Mocek and Drzymała (2010) report that the low solubility of heavy metals is since, in an

alkaline environment, these elements readily form compounds that are difficult for plants to access. As a result of the research, it was found that the introduction of granulates A (pH_{KCl} = 8.8), B (pH_{KCl} = 7.9), C (pH_{KCl} = 10.0) and D (pH_{KCl} = 8.0) with alkaline properties into the soil contributed to a reduction in the solubility of most heavy metals, which results in a reduction in their uptake by plants.

The results of the study indicate that the main factors contributing to the increased heavy metal content in the tested soil were industrial sewage sludge and ash. This thesis is supported by studies (Kabata-Pendias, 2011) that showed that the increase in the total content depends on the chemical composition of the industrial sewage sludge and on the type of ash, as well as on the content of these elements in both wastes.

Table 7. Correlation coefficient (*r*), coefficient of determination (*R*²), and standard deviation (*SD*) between the total content and available form of P, K and Mg in the soil after harvesting the test plants

Element	Soil after rapeseed harvest			Soil after triticale harvest		
	<i>r</i>	<i>R</i> ²	<i>SD</i>	<i>r</i>	<i>R</i> ²	<i>SD</i>
P	0.9321	0.9029	±0.092	0.9624	0.9012	±0.097
K	0.7379	0.7989	±0.145	0.7862	0.7512	±0.140
Mg	0.8844	0.7977	±0.071	0.8654	0.7811	±0.076

Source: own study.

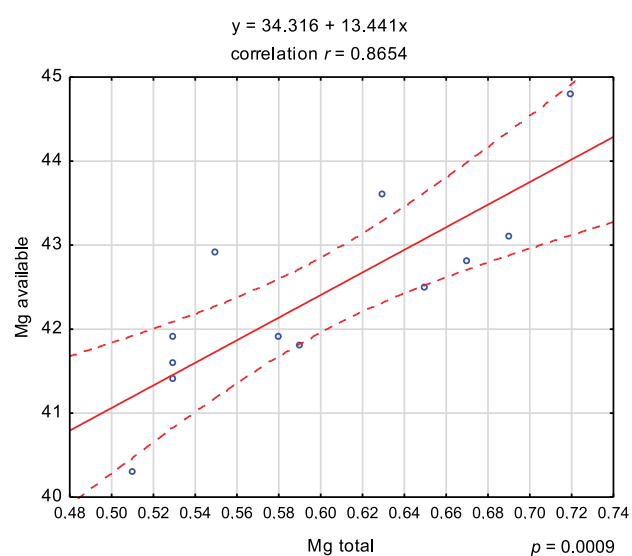
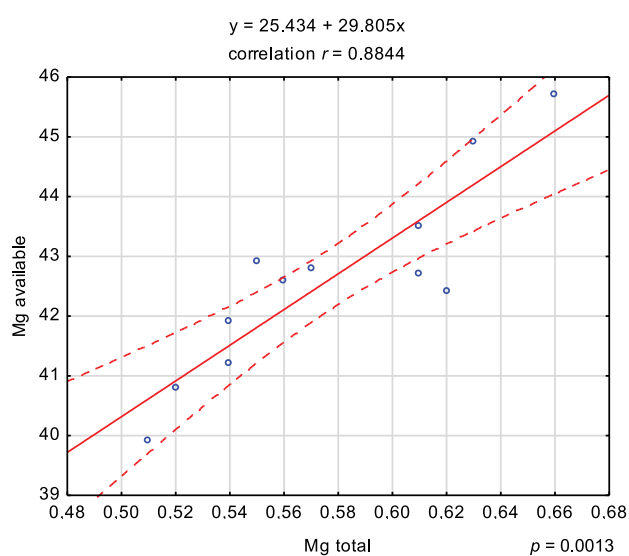
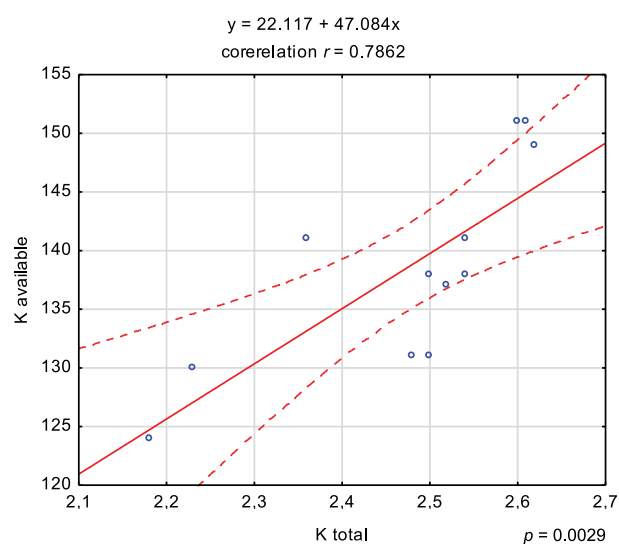
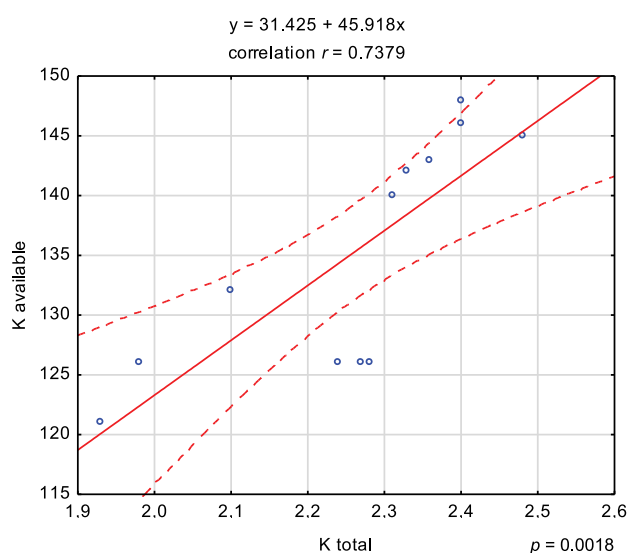
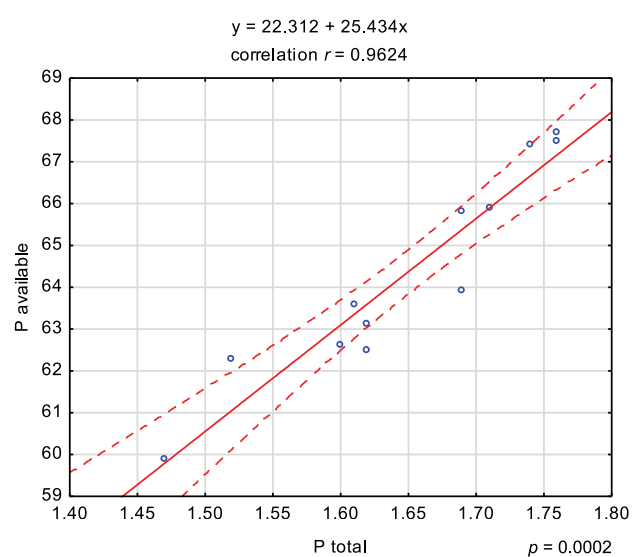
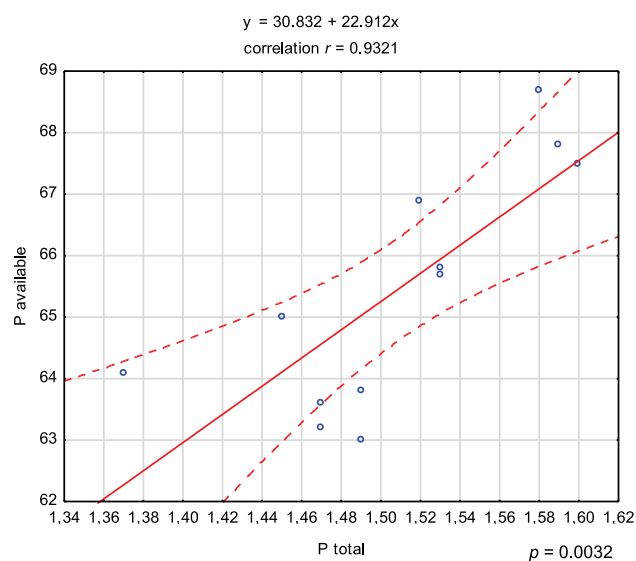


Fig. 1. Rectilinear relationship between the total and available content of P, K and Mg in the soil after rapeseed harvest under the influence of the applied fertiliser granulates; p = probability; source: own study

Fig. 2. Rectilinear relationship between the total and available content of P, K and Mg in the soil after triticale harvest under the influence of the applied fertiliser granulates; p = probability; source: own study

Taking into account the applied granulates A, B, C, and D and their doses, linear correlations were calculated between the total content and the assimilable forms of P, K, and Mg in the soil after harvesting the test plants (Tab. 7, Figs. 1, 2). The results of the study showed a significant relationship ($p < 0.05$) between the total content and the available form of the analysed elements. The calculations indicate that the highest positive correlation occurred between the total P content and the available P form in the soil after harvesting triticale and rapeseed. The calculated correlation coefficients were $r = 0.9321$ and $r = 0.9624$ for P, respectively. A high correlation was also found for Mg. A lower correlation was observed between total and available K content in the soil after rapeseed harvest ($r = 0.7379$ and $r = 0.7862$).

The coefficient of determination for K and Mg indicates that their content depended on the available form by 15.3 and 13.1%, respectively, and on other factors by 84.7 and 87.0%. Bielińska, Baran and Stankowski (2009) draw attention to the relationship between the content of P, K, and Mg in the soil and enzymatic activity. Statistical analysis of the research results confirmed significant relationships between the total content of K and Mg in the soil and their available forms.

In summary, the practical usefulness of applying fertiliser granulates produced from industrial sewage sludge, ash and sawdust used in the experiment for agricultural purposes can be demonstrated. Furthermore, the recovery of the basic nutrients N, P, K, Ca, Mg and S from the above-mentioned mineral and organic wastes enables their sustainable use, and the macronutrients can be reused in the production cycle. Therefore, the research carried out aligns with the European Union's Circular Economy Action Plan (Communication, 2020), which encourages the use of waste as fertiliser.

In order to further the research, it is planned to investigate alternative combinations for the production of fertiliser granules or mixtures, e.g. from industrial sewage sludge, used mushroom substrates and ash, or municipal sewage sludge, digestate and ash, and to determine the optimal doses for cultivated plants and their use, as well as to support sustainable waste management.

CONCLUSIONS

1. The effects of the tested granulates A, B, C and D on soil fertility indicators depended on the properties and percentage shares of the individual wastes used to produce them.
2. The applied granulates A, B, C and D caused an increase in soil pH, increased the total content of macronutrients and assimilable forms of P, K and Mg in the tested soil compared to the control.
3. Granulate C had the greatest effect on the increase in the concentration of P, K, Ca, Mg and S, and granulate D on the increase of Cu, Cd, Zn and Cr in the soil after harvesting both test plants.
4. The studies showed that the soil available K content after harvesting both test plants increased with increasing applied doses of granulates, allowing it to be classified as high in this element, whereas before the experiment, it was classified as medium.
5. The third dose of granulates A, B, C and D used applied had the greatest impact on the increase in the content of macronutrients, heavy metals and assimilable forms of P, K and Mg in the tested soil.

6. There is a correlation between the total content and the bio-available forms of P, K and Mg in the soil following the application of the tested fertiliser granulates.

ACKNOWLEDGEMENTS

The study was partially carried out as part of the research project financed by the Ministry of Science and Higher Education NCN no. N 305 358739 "Research on the use of industrial waste for the production of organic-mineral fertilisers and their impact on the soil environment and the quality of plant crops" and the West Pomeranian University of Technology in Szczecin under the UPB (Maintaining the Research Potential).

FUNDING

The research was partially financed by research project NCN no. N 305 358739 and the West Pomeranian University of Technology in Szczecin under the UPB (Maintaining the Research Potential) research no 503-008090-09.

CONFLICTS OF INTEREST

The author declares no conflict of interests.

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