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ORIGINAL PAPER

EFFECT OF HIGH PIG SLURRY DOSES ON YIELDS AND IONIC BALANCE OF WHITE MUSTARD

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ABSTRACT

The simplification of crop rotation systems, an increase in the concentration of cultivated cereals, and intensification of animal production in litter-free farms have drastically reduced the pig manure production. The consequences include negative organic matter balance and considerable leaching of mineral components from fields. The objective of this paper is to assess the effect of high doses of pig slurry on plants, and to analyse the ionic balance of white mustard. The experiment was conducted in four replications. Test plots were treated with pig slurry at doses of 0, 30, 60, and 90 tonnes fresh mass per hectare. Then, white mustard was sown. After the harvest, the plant material was separated into grains, husks, and stalks. The following were determined in the organic material: total nitrogen, cations (Ca, Mg, K, Na), phosphorus, and total organic acids. The ionic composition of particular parts of plants showed considerable differences associated with different life functions of these plant organs. In grains and stalks of mustard, the ratio of bivalent (Ca+Mg) to monovalent cations (K+Na) showed no considerable variations and was approximate to one. It was only in husks that bivalent cations were three times more abundant that monovalent cations. A considerable increase in yields was observed with an increase in pig slurry doses. The analysis showed the highest accumulation of Ca and K in husks, and the accumulation of mostly N, P, and Mg in grains. During the crop cultivation, approximately 20% of nutrients absorbed by plants from the soil are removed in the form of useful yield, that is grains. The remaining plant parts are ploughed as organic matter, providing nutrients to successive crops through its slow mineralisation over several years.

Keywords: white mustard, pig slurry, yield, ionic balance of plants.

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INTRODUCTION

Owing to its rapid and substantial biomass growth, white mustard *(Sinapis alba)* is a plant cultivated both as the main crop and an intercrop. The plant tolerates high doses of both mineral and organic fertilisers, particularly pig slurry. It is also appreciated for its ability to inhibit the development of potato cyst nematodes in soil (Wilczewski 2004, Sawicka, Kotiuk 2007, Nowakowski, Franke 2013). Losses of mineral components from fields and negative organic matter balance have been observed in Poland in recent years (Wilczewski et al. 2019). The situation is associated with an increase in land area cropped with cereals as well as a higher number of farmsteads without livestock raised on litter, causing a considerable reduction of pig manure production (Kisielewska, Harasimowicz-Herman 2008, Wojciechowska, Wermińska 2016). Large pig and dairy cattle farms in no-litter barns and pigsties result in difficulties managing the resulting high volumes of pig slurry and manure. Therefore, this study attempts to assess the effect of applying relatively high doses of pig slurry from pig farms on soils and plants.

MATERIALS AND METHODS

The experiment was conducted on soil developed from sandy boulder loam. The soil used in the experiment had the grain-size composition of sandy loam PTG (2009), and its total organic carbon ranged from 10.8 to 11.0 g kg^{-1}. It had neutral reaction and the pH values determined in 1M KCl ranged from 6.6 to 6.8. The values of cation exchange capacity of the soil were from 23.1 to 23.5 mmol(+) kg^{-1}. Plots with an area of 2x2 m=4 m^2 were encased with concrete, like lysimeters, down to a depth of 50 cm, in order to prevent pig slurry permeation to the neighbouring plots. Pig slurry doses were as follows: 0, 30, 60, and 90 tonnes fresh mass per hectare.

After pig slurry had permeated into the soil, i.e. after two weeks, the soil was dug over to a depth of 25 cm. White mustard seeds of the Metex variety were sown in early May and harvested at full maturity in the second half of August. The analysis of plant material was conducted in accordance with the methods of De Wit et al. (1963) and Van Tuil et al. (1964). After air-drying, the plants were separated into grains, husks, and stalks. These three parts were dried to constant weight separately in a dryer set at a temp. of 70°C. Then, one-gram samples were incinerated in a muffle furnace at 500°C, also to constant weight. The ash was dissolved in 25 ml 0.2 M of hot HCl in crucibles and filtered through medium density filters to 100 ml culture flasks. Sediment on filters was rinsed with hot hydrochloric acid. The flasks were supplemented with distilled water and the content was stirred.

After several days, Ca, Mg, K, and Na were determined by means of the AAS method. Phosphorus was determined by the colorimetric method with ammonium molybdate, zinc chloride, and menthol (monomethyl-*p*-aminophenol), according to Brogowski (1966). Nitrogen was determined by the Kjeldahl method. Total content of organic acids (organic anions – $R\text{-}COO^-$) was determined in separate samples of particular parts of white mustard, also by incinerating 1-gram samples at 500°C in accordance with the method of Van Tuil (1965). Total ions SO_4^{2-}+ Cl^-+NO_3^- were calculated based on the difference (Ca^{+2}, Mg^{+2}, K^+, Na^+)-($R\text{-}COO^-$+ $H_2PO_4^-$) in accordance with the same method.

Content of exchangeable cations (in 1 M ammonium acetate with pH=7), and the content of organic carbon (by the Tiurin method) in soil samples were determined two weeks after applying pig slurry. The determinations enabled us to verify how much of the nutrients was expended with the harvest, and to determine the rate of organic matter mineralisation.

Pig slurry used in the experiment contained 102.0 g kg^{-1} of dry mass. Content of organic matter in dry matter was 830.0 g kg^{-1}, ash 170.0 g kg^{-1} and organic carbon 474.0 g kg^{-1}. Content of minerals was as follows: Ca – 2.7 g kg^{-1}, Mg – 0.4 g kg^{-1}, K – 1.1 g kg^{-1}, P – 1.6 g kg^{-1}, and N – 2.4 g kg^{-1} in fresh mass.

Multivariate analysis of variance (MANOVA) was performed to verify the significance of the effect of different pig slurry doses on the composition of particular parts of plants. The factors were pig slurry doses (at four levels: 0, 30, 60, and 90 t ha^{-1}), part of plants (three levels: grains, stalks, husks), and their mutual interactions. Dependent variables included a set of data regarding yield, ash, and content of Ca^{2+}, Mg^{2+}, K^+, Na^+, $R\text{-}COO^-$, $H_2PO_4^-$, and N. The next step involved the determination of the significance of the effect of these factors on each trait separately. It was composed of a series of two-factorial analyses of variance (ANOVA), with factors identical as in the MANOVA analysis, and having a single analysed trait as the dependent variable. If the significance of the effect of a factor was confirmed, a division into homogenous groups was performed by the Tukey test. If the interaction was significant, the division into groups for one factor was performed at a specified level of the other factor. Data on total mustard yield and absorbed nutrients were presented in a PCA biplot. One factor in this analysis was a pig slurry dose, and the other was a plant trait. Values of each trait were standardised.

The calculations were performed in the R CORE TEAM (2019) environment. The multivariate analysis of variance (MANOVA) was performed with the help of the ‘manova’ function in the ‘STATS’ package. The analyses of variance were conducted by the ‘lm’ function. The Tukey test was based on the ‘HSD.test’ function of the ‘Agricolae’ package. A PCA biplot was prepared in accordance with the algorithm provided by Sienkiewicz-Paderewska, Paderewski (2015).

RESULTS AND DISCUSSION

The multivariate analysis of variance (MANOVA) showed different ionic compositions for different parts of mustard (Table 1). The level of pig slurry

Table 1

Multivariate analysis of variance (MANOVA) for yield, ash, and content of Ca^{2+}, Mg^{2+}, K^{+}, Na^{+} R-COO^{-}, $H_2PO_4^{-}$, N

Source	Df	Pillai value	*F*	*P*
Dose of pig slurry	3	2.97	290	<=0.001
Part of plants	2	2.00	49102	<=0.001
Dose × part of plant	6	5.67	63	<=0.001
Residuals	36			

Df – degrees of freedom, *F* – value of statistic based on *F*-test, *P* – observed significance level (*P*-value)

application differentiated parameters measured in mustard plants, and the effect of the doses was different for different parts of the plant. Therefore, it was justified to perform an analysis of variance (ANOVA) for each analysed trait separately. All these analyses confirmed the significance of the main effects of a pig slurry dose, main effects of a part of the plant, and effects of the interactions between these factors on each of the analysed traits (Tables 2, 3). Therefore, the effect of a pig slurry dose on each of the traits had to be analysed for each part of the plant separately.

Yielding of white mustard considerably increased as a result of pig slurry application in comparison to the zero combination with no additional mineral fertilisation after the application of pig slurry (Table 4). Evidently lower yields of mustard (4.39 t ha^{-1} on average) fertilised with cattle manure were reported by Wilczewski (2004), although in that study mustard was cultivated as stubble intercrop, which considerably shortens the plant growing period. The yield of grains increased the most, from 4.4 times at a dose of 30 t ha^{-1} of pig slurry to 6.0 times at 90 t ha^{-1}. Each level of pig slurry application significantly increased grain yield. Stalk yield increased from 3.3 to 5.7 times (whereas the effect of doses 30 and 60 was not statistically significant), and husk yield rose from 4.5 to 5.2 times in comparison to the zero combination (Table 4, Figure 1). Husk yield was the lowest in the treatment without pig slurry, and highest in response to the dose of 90 t ha^{-1}. Husk yield was the highest, stalk yield was statistically lower, and grain yield was the lowest (Table 5). The exception was a dose of 60 t ha^{-1}, in response to which grain and stalk yield showed no significant difference.

The percentage of particular parts of white mustard harvest in total yield (grains + stalks + husks = 100%) averaged: grains – 21.1%, stalks – 27.2%, and husks – 51.7%, with small variations for particular fertiliser combinations (Figure 2). Therefore, the basic yield (grains) in white mustard

Table 2

Analyses of variance (ANOVA) – tables for single parameters of the plant

Specification		Yield			Ash			Ca^{2+}		
Source	Df	SS	*F* value	*P*	SS	*F* value	*P*	SS	*F* value	*P*
Dose of pig slurry	3	4741	4289	<=0.001	12.1	489	<=0.001	2599	605	<=0.001
Part of plant	2	3560	4831	<=0.001	537.7	32637	<=0.001	161017	56256	<=0.001
Dose × part of plant	6	799	362	<=0.001	36.8	745	<=0.001	2931	341.4	<=0.001
Residuals	36	13			0.3			52		
		Mg^{2+}			K^{+}			Na^{+}		
Dose of pig slurry	3	157.0	596	<=0.001	182.3	173	<=0.001	8.5	52	<=0.001
Part of plant	2	2699.4	15376	<=0.001	2379.8	3392	<=0.001	360.6	3312	<=0.001
Dose × part of plant	6	79.2	150	<=0.001	671.7	319	<=0.001	10.0	31	<=0.001
Residuals	36	3.2			12.6			2.0		
		$R\text{-}COO^{-}$			$H_2PO_4^{-}$			N		
Dose of pig slurry	3	1127	2293	<=0.001	201	855	<=0.001	581	457	<=0.001
Part of plant	2	133333	406777	<=0.001	4943	31549	<=0.001	369242	435114	<=0.001
Dose × part of plant	6	1560	1586	<=0.001	78	166	<=0.001	147	58	<=0.001
Residuals	36	6			3			15		

SS – sum of squares

Table 3

Analyses of variance (ANOVA) – tables for complex parameters of the plant

Specification		Ca+Mg+K+Na			Ca+Mg:K+Na			SO^{2+}+Cl^{-}+NO		
Source	Df	SS	*F* value	*P*	SS	*F* value	*P*	SS	*F* value	*P*
Dose of pig slurry	3	2325	416.4	<=0.001	0.25	54.5	<=0.001	1896.8	7958	<=0.001
Part of plant	2	141272	37949.4	<=0.001	57.79	19070.5	<=0.001	2745.4	17279	<=0.001
Dose × part of plant	6	3454	309.3	<=0.001	0.88	97.3	<=0.001	1677.0	3518	<=0.001
Residuals	36	67			0.05			2.9		
		K:N			K:Ca+Mg					
Source	Df	SS	*F* value	*P*	SS	*F* value	*P*			
Dose of pig slurry	3	3.11	667.8	<=0.001	0.027	77.0	<=0.001			
Part of plant	2	180.20	58076.5	<=0.001	5.710	24765.5	<=0.001			
Dose × part of plant	6	2.53	271.4	<=0.001	0.596	862.2	<=0.001			
Residuals	36	0.06			0.004					

Table 4

Ionic composition of parts of white mustard with homogeneous groups of impact of doses on ionic composition for each part of the plant

Doses of pig slurry fresh mass (t ha^{-1})	Parts of plants	Yield (dt ha^{-1})	Ash (g kg^{-1})	mmol(+) kg^{-1} d.m. cations					K:(Ca+Mg)	(Ca+Mg):(K+Na)	mmol(+) kg^{-1} d.m. anions			N	∑K:N
				Ca^{2+}	Mg^{2+}	K^+	Na^+	∑= Ca+Mg+K+Na			R-COO$^-$	$H_2PO_4^-$	$SO_4^{2-}+Cl^-+NO_3^-$		
0	grains	3.4^d	58.5^b	237.0^a	183.0^b	470.0^a	8.0^a	898.0^a	1.12^a	0.88^b	405.0^a	273.0^b	220.0^a	2184.0^d	0.41^a
30	grains	14.9^c	54.4^c	225.0^{ab}	175.0^c	423.0^b	7.0^a	830.0^b	1.05^b	0.93^b	362.0^c	315.0^a	153.0^c	2200.0^c	0.38^a
60	grains	18.1^b	61.0^a	234.0^a	229.0^a	418.0^b	6.0^a	887.0^a	0.88^c	1.09^a	391.0^b	315.0^a	181.0^b	2274.0^b	0.39^a
90	grains	20.3^a	56.7^b	205.0^b	235.0^a	382.0^c	3.0^a	825.0^b	0.86^c	1.14^a	320.0^d	321.0^a	184.0^b	2306.0^a	0.36^a
-	-	-	57.6	225.0	206.0	423.0	6.0	860.0	0.98	1.01	370.0	306.0	184.0	2241.0	0.38
0	stalks	5.3^c	68.0^c	567.0^a	30.0^a	543.0^c	67.0^b	1207.0^{bc}	0.91^b	0.98^a	800.0^d	50.0^d	357.0^a	243.0^b	4.97^a
30	stalks	17.8^b	68.0^c	562.0^a	30.0^a	521.0^d	69.0^b	1182.0^c	0.88^c	1.00^a	867.0^c	58.0^c	257.0^b	237.0^b	4.99^a
60	stalks	18.1^b	77.5^a	509.0^b	34.0^a	660.0^a	86.0^a	1289.0^a	1.21^a	0.73^b	970.0^a	85.0^a	234.0^c	263.0^a	4.90^a
90	stalks	30.5^a	73.6^b	494.0^b	33.0^a	641.0^b	68.0^b	1236.0^b	1.22^a	0.74^b	902.0^b	74.0^b	260.0^b	274.0^a	4.51^b
-	-	-	71.8	533.0	32.0	59.1	73.0	1229.0	1.05	0.86	885.0	67.0	277.0	254.0	4.84
0	husks	9.3^d	150.0^a	1856.0^a	27.0^c	485.0^b	40.0^a	2408.0^a	0.26^b	3.59^a	1772.0^a	96.0^c	540.0^a	524.0^c	4.60^a
30	husks	41.7^b	148.2^a	1583.0^b	56.0^b	480.0^b	22.0^b	2141.0^b	0.29^a	3.26^b	1573.0^c	93.0^c	475.0^b	486.0^d	4.40^b
60	husks	36.2^c	132.4^b	1529.0^c	95.0^a	500.0^a	36.0^a	2160.0^b	0.31^a	3.03^d	1747.0^b	173.0^a	240.0^c	546.0^b	3.96^c
90	husks	48.9^a	108.0^c	1346.0^d	90.0^a	428.0^c	27.0^b	1891.0^c	0.30^a	3.15^c	1517.0^d	150.0^b	224.0^d	602.0^a	3.14^d
-	-	-	134.6	1579.0	67.0	473.0	31.0	2150.0	0.29	3.26	1652.0	128.0	370.0	540.0	4.02

a.b.c.d – Homogeneous groups according the Tukey test of the impact of doses on single traits for each part of the plant separately,
∑K:N – The ratio of the sum of cations to nitrogen

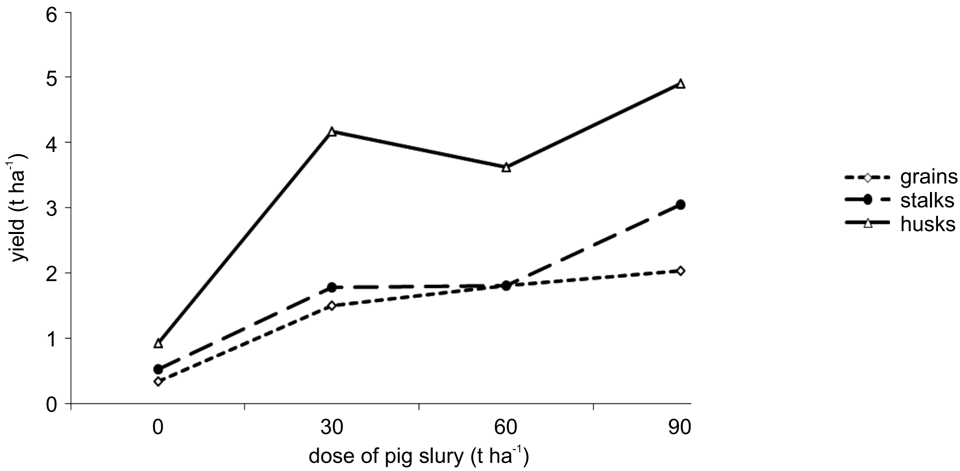

Fig. 1. Effect of pig slurry doses on yield of particular parts of mustard

constituted one fifth of total yield, and the remaining parts (stalks + husks) combined made up approximately 80% of total yield. This part is usually left in the field and ploughed.

Ash content in particular parts of mustard yield was considerably (Table 4) and significantly (Table 5) variable, and the ranking of parts of plants by this trait was not dependent on a fertiliser combination (Table 5). In husks, the ash content depended on fertilisation, i.e. it was the highest at the doses of 0 and 30 t ha^{-1}, significantly lower at the dose of 60 t ha^{-1}, and the lowest at the dose of 90 t ha^{-1} (Table 4). For stalks, the lowest ash content was recorded in treatments with the doses of 0 and 30 t ha^{-1}. The ash content was the lowest in mustard grains, and the highest in husks. In stalks, the ash content was higher than in grains by approximately 25 g kg^{-1}, and in husks - by as much as 77 g kg^{-1} (Table 4). The ash content in particular parts of mustard depends on the functions fulfilled in the plant as a total of its components.

Cations (Ca + Mg + K + Na) were distributed in particular parts of mustard in highly variable quantities (Table 4). Like in the case of yield and ash content, the highest amount of cations was determined in husks, significantly lower in stalks, and the lowest in grains. This dependency (and its statistical significance) was repeated for each fertiliser dose (Table 5). In husks, the highest amount of cations was determined in the cultivation treatment without pig slurry, the lowest at the dose of 90 t ha^{-1}, and moderate at the doses of 30 and 60 t ha^{-1} (not statistically significant) (Table 4). For grains, the cation content was higher for doses of 0 and 60 t ha^{-1} than for doses of 30 and 90 t ha^{-1}.

Like ash and cations (Ca+Mg+K+Na), calcium was primarily accumulated in husks, in lower quantities in stalks, and the least calcium was in grains

Table 5

Homogeneous groups of parts of white mustard according to the Tukey test of considered traits for each slurry dose separately

Trait	Parts of plants	Dose 0	Dose 30	Dose 60	Dose 90	Trait	Parts of plants	Dose 0	Dose 30	Dose 60	Dose 90
Yield	grains	*c*	*c*	*b*	*c*	K:(Ca+Mg)	grains	*a*	*a*	*b*	*b*
	stalks	*b*	*b*	*b*	*b*		stalks	*b*	*b*	*a*	*a*
	husks	*a*	*a*	*a*	*a*		husks	*c*	*c*	*c*	*c*
Ash	grains	*c*	*c*	*c*	*c*	(Ca+Mg):(K+Na)	grains	*c*	*c*	*b*	*b*
	stalks	*b*	*b*	*b*	*b*		stalks	*b*	*b*	*c*	*c*
	husks	*a*	*a*	*a*	*a*		husks	*a*	*a*	*a*	*a*
Ca^{++}	grains	*c*	*c*	*c*	*c*	$R\text{-}COO^{-}$	grains	*c*	*c*	*c*	*c*
	stalks	*b*	*b*	*b*	*b*		stalks	*b*	*b*	*b*	*b*
	husks	*a*	*a*	*a*	*a*		husks	*a*	*a*	*a*	*a*
Mg^{++}	grains	*a*	*a*	*a*	*a*	$H_2PO_4^-$	grains	*a*	*a*	*a*	*a*
	stalks	*b*	*c*	*c*	*c*		stalks	*c*	*c*	*c*	*c*
	husks	*b*	*b*	*b*	*b*		husks	*b*	*b*	*b*	*b*
K^+	grains	*c*	*c*	*c*	*c*	$SO_4^{2-}+Cl^-+NO_3^-$	grains	*c*	*c*	*c*	*c*
	stalks	*a*	*a*	*a*	*a*		stalks	*b*	*b*	*b*	*a*
	husks	*b*	*b*	*b*	*b*		husks	*a*	*a*	*a*	*b*
Na^+	grains	*c*	*c*	*c*	*c*	N	grains	*a*	*a*	*a*	*a*
	stalks	*a*	*a*	*a*	*a*		stalks	*c*	*c*	*c*	*c*
	husks	*b*	*b*	*b*	*b*		husks	*b*	*b*	*b*	*b*
Ca+Mg+K+Na	grains	*c*	*c*	*c*	*c*	$\sum K:N$	grains	*c*	*c*	*c*	*c*
	stalks	*b*	*b*	*b*	*b*		stalks	*a*	*a*	*a*	*a*
	husks	*a*	*a*	*a*	*a*		husks	*b*	*b*	*b*	*b*

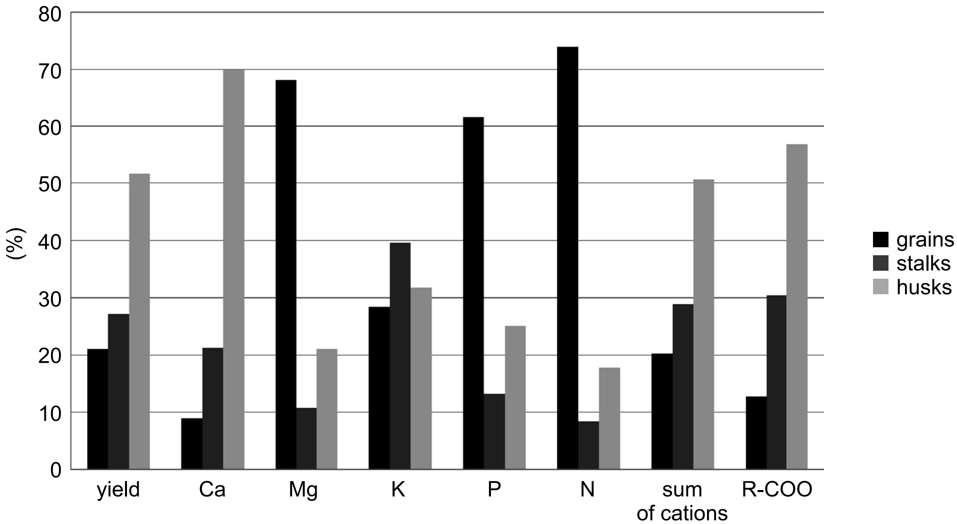

Fig. 2. Precent share of particular parts of mustard in the accumulation of elements. Total yield (grains+stalks+husks) and share of a given element in total yield=100%

of mustard (Table 5). Stalks accumulated an average of 2.3 times more calcium than grains, and husks 7 times more (Table 4). In grains and stalks, the calcium content was approximately constant, although in grains, the dose of 90 t ha^{-1} caused a significantly lower (Table 4) calcium content than the doses of 0 and 60 t ha^{-1}, and in stalks the doses of 90 and 60 t ha^{-1} (with no statistically significant difference) caused significantly lower calcium content than doses of 30 and 0 t ha^{-1}. In husks, the content of this element significantly decreased with an increase in pig slurry doses. The calcium content in this part of mustard increased with the ash content and decreased with an increase in the magnesium content. Approximate proportions of the calcium content in grains to its content in straw were reported by Maciejewska and Kwiatkowska (2001), who determined that the straw contained approximately 4.5 times more calcium than grains after the application of mineral-organic fertiliser.

Assuming the calcium content in equivalent values throughout the plant (grains + stalks + husks) to constitute 100%, grains contained approximately 9.7%, stalks 22.9%, and husks 67.4% of the element (Figure 2).

Because only grains are used for consumption, whereas stalks and husks after harvest are left in the field and ploughed, they constitute a fertiliser with high calcium content from approximately 40 to 160 kg Ca ha^{-1} (Table 6). In comparison to rape, mustard (grains, stalks, and particularly husks) is richer in this element (Brogowski et al. 1995).

Magnesium was distributed in particular parts of mustard in a completely different way than calcium and the previously discussed elements (Table 4). Its content was the lowest in stalks, significantly higher in husks (with the exception of the cultivation treatment without pig slurry, where the diffe-

Table 6

Uptake of elements from the soil by particular parts of white mustard yield

Doses of pig slurry fresh mass (t ha^{-1})	Part of plant	Ash	Ca	Mg	K	Na	P[#]	N	Total
		(kg ha^{-1})							
0	grains	20.0	1.6	0.8	6.2	0.1	0.9	10.4	20.0
30		81.0	6.7	3.2	24.6	0.2	4.6	45.9	85.2
60		110.4	8.5	5.0	29.5	0.3	5.6	57.6	106.5
90		115.1	9.4	5.8	34.3	0.2	6.5	65.5	121.7
0	stalks	36.0	6.0	0.2	11.2	0.8	0.3	1.8	20.3
30		121.0	19.9	0.6	36.1	2.8	1.0	5.9	66.3
60		140.3	18.5	0.7	46.5	3.6	1.5	6.7	77.5
90		224.5	30.2	1.2	76.3	4.8	2.1	11.7	126.2
0	husks	139.5	34.5	0.3	17.6	0.8	0.9	6.8	60.9
30		618.0	132.0	2.8	78.1	2.1	4.0	28.3	247.3
60		479.3	110.8	4.2	70.6	3.0	6.2	27.7	222.5
90		528.1	131.5	5.3	81.6	3.0	7.2	41.2	264.8

[#] The calculation was based on pure phosphorus, not anion H_2PO_4.

rence was not statistically significant), and the highest in grains (Table 5). In grains and husks, the magnesium content was the highest at the doses of 90 and 60 t ha^{-1} (Table 4), significantly lower at the doses of 30 and 0 t ha^{-1}, while in stalks the magnesium content changed only in a small range. Likewise, considerably higher magnesium accumulation was determined in grains than in straw in the study by Maciejewska and Kwiatkowska (2001). The distribution of magnesium in particular parts of mustard was as follows: on average, grains accumulated 68.2% of total magnesium, stalks only 10.7%, and husks 21.1% (Figure 2). Quantitative fluctuations related to pig slurry doses were considerably higher than for calcium. The Mg content in particular parts of mustard was approximate to that in oilseed rape (Brogowski et al. 1995).

Potassium was distributed in mustard more evenly, with slight prevalence in stalks. Different results were reported by Maciejewska and Kwiatkowska (2001), pointing to an approximately twice as high potassium accumulation in straw as in grains. Quantitative fluctuations related to pig slurry doses did not exceed 300 g kg^{-1} (Table 4). For all pig slurry doses, the potassium content was the highest in stalks, significantly lower in husks, and the lowest in grains (Table 5). In grains, its content slightly decreased with an increase in pig slurry doses, and in stalks it increased to a similar degree to which it decreases in mustard grains. On average, the percent share of particular parts of mustard in potassium accumulation was slightly variable with slight prevalence in stalks. Grains accumulated a chemically equivalent average of 28.5%, stalks 39.7%, and husks 31.8% (Figure 2).

Sodium occurred in small amounts, particularly in grains. Somewhat higher accumulation of the element was observed in stalks, and half lower in husks (Table 4). This pattern was repeated for all doses, and was statistically significant, as in the case of potassium (Table 5).

Total base cations (Ca + Mg + K + Na) in the analysed plant were significantly (Table 5) lowest in grains, varying from 825.0 to 898.0 mmol(+) kg^{-1} (Table 4). Stalks were on average richer in base cations than grains by approximately 369.0 mmol(+) kg^{-1}, and husks even richer, by 1290.0 mmol(+) kg^{-1} in comparison to grains. The order of parts of plants in terms of the abundance of cations was therefore identical (Table 5) as for yield, ash, $R\text{-}COO^{-}$, and total anions. In grains and stalks, total cations were the lowest at the pig slurry dose of 60 t ha^{-1}, and in husks they decreased with an increase in doses (Table 1).

The percent share in the accumulation of total cations in particular parts of mustard yield increased from grains through stalks to husks. Grains accumulated an average of 20.3% for all fertiliser combinations with variation from 19.9 to 20.9%. These values increased from the zero dose of pig slurry to 90 t ha^{-1}. Stalks accumulated somewhat higher amounts of cations, 29.1% on average, with variation from 26.7 to 31.3%. Their share also increased from the zero dose to the dose of 90 t ha^{-1} of pig slurry (Figure 2). Base cations were primarily accumulated in husks, averaging 50.6% of total cations in the plant, whereas an increase in pig slurry doses caused a decrease in the share of cations in husks reversely to that in grains and stalks. Such distribution of base cations in mustard was probably a result of yielding. Low yield in the zero combination increased the content of cations, but only in husks, at the cost of grains and stalks.

According to many authors who have analysed relationships between concentrations of macronutrients in plants, appropriate ratios between these elements largely determine many physiological and biochemical processes occurring in plants Możdżer and Stryczula (2019), Szpunar-Krok et al. (2009), Redaelli et al. (2009). In this study, the ratio of bi- to monovalent cations in grains was balanced and oscillated around one. It was lower than one in stalks and decreased with an increase in pig slurry doses (Table 4). Doses of 0 and 30 t ha^{-1} had a considerably higher index than 60 and 90 t ha^{-1}. The situation was opposite for grains, where both lower doses caused lower values of the index than either of the higher pig slurry doses. The ratio lower than one was caused by higher potassium content in this part of mustard. The broadest ratio averaging 3.2 with small variation was observed in husks. In this part of the plant, the highest values were recorded in the treatment without pig slurry, significantly lower at the dose of 30 t ha^{-1}, and even lower at the doses of 90 and 60 t ha^{-1}. The ratio in the entire plant based on weighted average was 2.08. It is in accordance with the theory that dicotyledonous plants show dominance of bivalent over monovalent elements, whereas monocotyledonous plants show the opposite pattern (Brogowski, Czępińska-Kamińska 2013). The ratio of K:(Ca+Mg) both in grains and stalks varied from 0.87 to 1.22, and in husks it was very narrow, averaging 0.29. In grains, an increase in pig slurry dose narrowed the ratio while broadening it in stalks. The study by Maciejewska and Kwiatkowska (2001) showed a somewhat broader ratio of the analysed cations both in grains (average 1.63) and in straw (average 1.21), as well as the narrowing of the ratio in grains with an increase in the applied fertiliser doses.

Mineral and organic anions showed quantitative variability in particular parts of mustard, and their total quantity was equal to total cations, corresponding with ionic balance in the plant as described by De Witt et al. (1963) – Table 4.

Among mineral anions, the dominant role in mustard is fulfilled by phosphorus, which is less abundant in husks, and the least abundant in stalks. The significance of differences was repeated for each fertiliser dose (Table 5). Quantities of phosphorus increased in all parts of mustard with increasing pig slurry doses (Table 4), although significantly more phosphorus was recorded in stalks and husks at the dose of 60 than at 90 t ha^{-1}. The phosphorus content in grains was approximately the same, although cultivation without pig slurry resulted in its significantly lower content. The percent share of phosphorus in particular parts of mustard was approximate to that of nitrogen and magnesium. Mustard grains accumulated an average of 61.7% of total phosphorus in the plant, with variation depending on a pig slurry dose from 55.0 to 67.6%, stalks on average 13.2% with variation from 11.9 to 14.8%, and husks 25.1% with variation from 22.9 to 30.2% (Figure 2). Grains and husks showed high fluctuations of phosphorus accumulation in different experimental combinations.

In mustard grains, mineral anions dominated over organic anions, while organic anions were dominant in the remaining parts of the plant. This results from different physiological functions of these two groups of anions in particular parts of the plant. The total content of mineral anions ($H_2PO_4^-$ $+SO_4^{2-}+NO_3^-+Cl^-$) in grains and stalks usually remained at an approximately constant level, irrespective of a pig slurry dose, but in husks it decreased distinctly with an increase in fertilisation. All the remaining anions ($SO_4^{2-}+$ $Cl^-+ NO_3^-$) and organic anions – R-COO^- decreased in quantity with an increase in pig slurry doses, except organic anions in stalks (Table 4).

Organic anions – organic acids in mustard husks constituted 57.0% of their total content in the entire plant, 30.5% in stalks, and only 12.7% on average in grains. Mineral anions (SO_4+Cl+NO_3) in husks averaged 44.6%, in stalks 33.3%, and in grains 22.1% (Figure 2). Both R-COO^- and total anions (SO_4+Cl+NO_3) occurred in the highest amounts in husks, lower in stalks, and the lowest in grains (Table 5). This dependency repeated for all doses with the exception of 90, for which the highest total anions (SO_4+Cl+NO_3) occurred in stalks, and significantly lower in husks.

According to Dutch studies by De Witt et al. (1963) and Van Tuil (1965), content of organic anions – organic acids is proportional to the yield of plant mass. In this study, quantities of mass produced by particular parts of mustard testify to this assumption (Table 4).

Total nitrogen in the plant can be collected from the soil both as cation -NH_4^+ and anion NO_3^-. Therefore, it is difficult to determine its side (cations – anions) in the calculations of ionic balance.

The highest nitrogen content usually occurs in grains, in this case – in mustard grains. Its significantly higher content was recorded in grains than in husks (Table 5), and the lowest values were determined in stalks. The average content of this element in grains was 2241 mmol(+) kg^{-1}, corresponding to 3.14%, and in conversion to raw protein – 19.6%. A small but significant (Table 4) increase in the element was observed in mustard grains with an increase in pig slurry doses. In the remaining parts of the analysed plant, the tendency was similar. Stalks accumulated less total nitrogen 254 mmol(+) kg^{-1}, and therefore protein, only 2.2% on average, and showed 8.8 times lower content of the element in comparison to grains. Husks contained twice as much nitrogen as stalks 540 mmol(+) kg^{-1}, and therefore more protein, namely 4.7% (Table 4). Both WILCZEWSKI and SKINDER (2005) and THORUP-KRISTENSEN (1994) revealed the ability of white mustard to accumulate nitrogen in aerial parts of plants, and therefore high usefulness of mustard for soil protection against the leaching of nitrogen in autumn and winter.

The percent share of particular parts of mustard in the accumulation of total nitrogen, and therefore protein, is highly variable. Grains accumulated an average of 73.9% of total nitrogen in the plant with small variations related to pig slurry dosage from 72.5 to 75.3%, stalks 8.4% with a variation from 8.1 to 8.6%, and husks 17.7% with a variation in different fertiliser combinations from 16.6 to 18.9% (Figure 2).

The ratio of cations absorbed by mustard and its parts to total nitrogen was relatively stable in the analysed plant organs. The average ratio in grains was 0.38, in stalks 4.84, and in husks 4.02 (Table 4). This suggests that stalks and husks, per one mmol(+) of nitrogen, used over ten times more base cations than grains. These parts (stalks and husks) of mustard managed nitrogen much more economically, while using Ca, Mg, K, and Na more wastefully than grains did.

Due to different life functions of particular parts of the plant, their ionic composition is distinctly varied. Assuming that the total macronutrients in particular parts of mustard, that is grains, stalks and husks, constitute 100%, the following sequences of their decreasing values are obtained, calculated from chemically equivalent and weight values in accordance with the average data:

in grains = N > K > P > Ca > Mg > Na = chemically equivalent;
N > P > K > Ca > Mg > Na = by weight;
in stalks = K > Ca > N > Na > P > Mg = chemically equivalent;
K > Ca > P > N > Na > Mg = by weight;
in husks = Ca > N > K > P > Mg > Na = chemically equivalent;
Ca > K > P > N > Mg > Na = by weight.

As shown above, a different element fulfils the primary role in each part of mustard, in accordance with its physiological function in a given part of the plant. In grains, total nitrogen - the primary component of protein in the generative part of the plant - is dominant. In stalks, the primary role is fulfilled by potassium. Its physiological function is to maintain stiffness. In husks, calcium contributes to the hardness of the capsule and provides protection against rapid changes in temperature.

The quantitative variability of an element is determined by its ratios in parts of the plant. The results according to electrochemically equivalent average data were as follows:

$N\ \frac{grain}{stalk} = 8.82$ $\quad$ $K\ \frac{grain}{stalk} = 0.72$

$N\ \frac{grain}{husk} = 4.20$ $\quad$ $K\ \frac{grain}{husk} = 0.89$

$P\ \frac{grain}{stalk} = 4.57$ $\quad$ $Ca\ \frac{grain}{stalk} = 0.42$

$P\ \frac{grain}{husk} = 2.40$ $\quad$ $Ca\ \frac{grain}{husk} = 0.14$

$Mg\ \frac{grain}{stalk} = 6.44$ $\quad$ $\text{total cations}\ \frac{grain}{stalk} = 0.70$

$Mg\ \frac{grain}{husk} = 3.07$ $\quad$ $\text{total cations}\ \frac{grain}{husk} = 0.40$

The above data show the evident dominance of three basic elements N, P, and Mg in grains (Figure 2), and Ca and K in stalks and husks.

Many researchers emphasise that the fertiliser value of plants results from the amount of produced biomass and the content of macronutrients (Zając, Antonkiewicz 2006, Wilczewski 2007, Zaniewicz-Bajkowska et al. 2013). Concerning the varied demand of parts of the plant, in this case mustard, for mineral components, their expenditure from the soil was calculated based on yields. It was determined that the highest amounts of Ca and K were accumulated in husks due to their highest yield and the highest content of these elements. Somewhat lower amounts of Ca and K were accumulated in stalks due to their lower yield and their lower content in mass. Grains accumulated high amounts of nitrogen, phosphorus, and magnesium, but due to their low yield in comparison to stalks and husks, the removal of these elements from the soil by grains was negligible (Tables 6 and 7). Therefore, considering that stalks and husks after harvest of mustard are left in the field and ploughed, the removal of nutrients from the soil by the plant is not so high. The applied pig slurry doses, by effecting differences in the plant yields, caused variability of the loss of calcium and potassium in the soil. The remaining elements showed no such variability. In the zero treatment and in the treatment with the dose of 30 t ha^{-1}, mustard depleted Ca the most and K to a somewhat lower degree. At the doses of 60 and

Table 7

Total yield (grains + stalks + husks) of mustard and elements collected from soil

Doses of pig slurry fresh mass (t ha^{-1})	Yield	Ca	Mg	K	Na	P	N	Σ	Yield[#]/Σ-m	Ca+Mg+K+Na+P:N	Ca+Mg:K+Na by weight
	(kg ha^{-1})										
0	1800	42.1	1.3	35.0	1.7	2.1	19.0	101.2	17.8	4.33	1.18
30	7440	158.6	6.6	138.8	5.1	9.6	80.1	398.8	18.7	3.98	1.15
60	7240	137.6	9.9	146.6	6.9	13.3	92.0	406.3	17.8	3.42	0.96
90	9970	171.1	12.3	192.2	8.0	15.8	118.4	517.8	19.2	3.37	0.91

[#] Total yield divided by total elements (Ca+Mg+K+Na+P+N).

90 t ha^{-1} of pig slurry, the highest loss concerned K, and somewhat lower Ca was removed from the soil (Table 7). The removal of N, P, and Mg by the mustard plant showed relatively little variability in proportion to their loss in the soil, in comparison to Ca and K. The depletion of mineral components from the soil by mustard depended on the plant's demand for nutrients to produce a mass unit. The production of a ton of dry matter in the aerial parts of mustard (grains + stalks + husks) required an average of 11.5 kg N, 20.2 kg Ca, 1.1 kg Mg, 19.4 kg K, 0.9 kg Na and 1.5 kg H_2PO_4. In total, all these nutrients constituted 54.6 kg t^{-1} of mustard. However, straw and husks remain in the field after harvest and are ploughed. Therefore, approximately 80% of the nutrients absorbed from the soil by mustard remained in the field, and the other 20% was collected from the farm in the form of useful yield, that is grains. According to numerous authors, cultivation of legumes as intercrops leaves from 50 to 100 kg ha^{-1} of nitrogen in the biomass (Rosolem et al. 2002, Balkcom and Reeves 2005). This means that cultivation of white mustard as an intercrop at high pig slurry doses would leave approximately same amounts of nitrogen in the field as the cultivation of legumes does (Table 7). Cultivation of mustard as the main crop would leave considerably less nitrogen in the field, i.e. approximately 30-50 kg ha^{-1} (Table 6).

Total yield (grains + stalks + husks) of mustard and the amounts of nutrients absorbed from the soil proved to be very strongly correlated. The biplot (Figure 3) shows approximately 96% variance for average values of the discussed traits in the entire plant at different pig slurry doses. The first component is evidently dominant, showing 89% variance. Clusters of points representing repetitions at the same pig slurry dose are strongly separated. Two parameters (Ca+Mg+K+Na+P)/N and (Ca+Mg)/(K+Na) proved to be strongly correlated. Higher values of these ratios were observed in the cultivation without pig slurry, somewhat higher for the dose of 30 t ha^{-1}, and even higher for the doses of 60 and 90 t ha^{-1}. Different values were obtained for the yield/total nutrients index. Higher values were obtained at the doses of 30 and 90 t ha^{-1}, and lower at the doses of 0 and 60 t ha^{-1}. The other analysed parameters were quite consistent, whereas the content of sodium, magnesium, and phosphorus provided for an identical order of the effect of doses. The highest values of these three elements

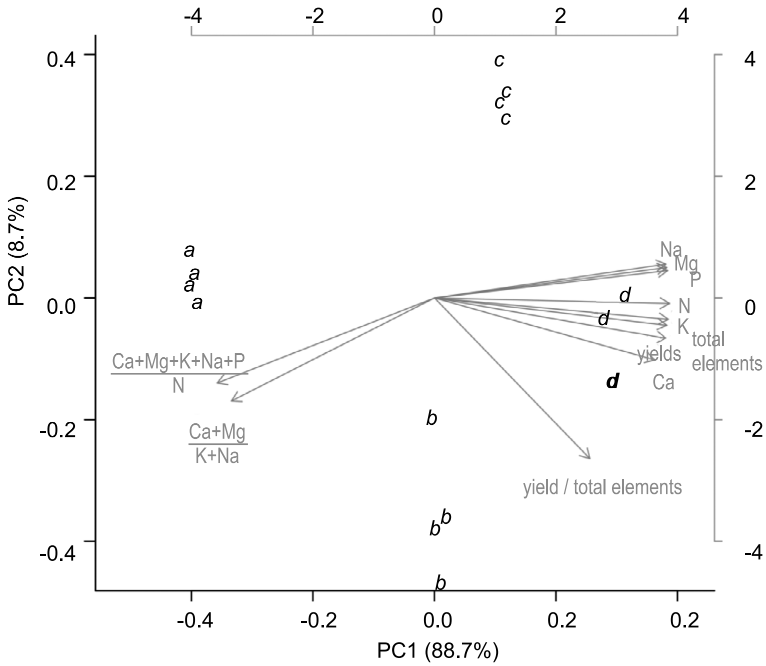

Fig. 3. Total yield (grains + stalk + husk) of mustard and elements absorbed from the soil presented in a PCA biplot. The variables were standardised: *a* – dose 0, *b* – dose 30 t ha^{-1}, *c* – dose 60 t ha^{-1}, d – dose 90 t ha^{-1}

occurred at the highest pig slurry dose. The situation was similar for such traits as the content of nitrogen, potassium, total nutrients or calcium. A decrease in the prevalence of the effect of a dose of 60 over a dose of 30 t ha^{-1} was observed for these parameters.

The above data suggest that such high doses of pig slurry will supply a pool of nutrients for several years, and total mineralisation of the introduced organic mass may last even 10 or more years. WILCZEWSKI and SKINDER (2005) proved that cultivation of mustard as a stubble intercrop caused a considerably higher accumulation of nitrogen and potassium in plant biomass higher than resulting from these macronutrients introduced to the soil as fertilisers.

CONCLUSIONS

1. The application of pig slurry caused a significant increase in yields of white mustard, its grains, stalks, and husks. It was only the yield of stalks that showed no significant difference at pig slurry doses of 30 and 60 t ha^{-1}.

2. Irrespective of fertilisation, three macronutrients were dominant in grains, such as nitrogen, phosphorus, and magnesium, while calcium and potassium dominated in husks and stalks.

3. In grains and stalks of mustard, the ratio of bivalent (Ca+Mg) to monovalent cations (K+Na) showed no considerable variation and was approximate to one. It was only in husks that bivalent cations were three times more abundant that monovalent cations.

4. The study showed that white mustard absorbs high amounts of nitrogen from the soil, thus providing substantial protection against the leaching of this microelement and can leave considerable amounts of this mineral in the field for subsequent crops (particularly if grown as intercrops).

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