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The Effects of Soil Application of Digestate Enriched with P, K, Mg and B on Yield and Processing Value of Sugar Beets

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Abstract: The aim of this research was to find out if the supplementation of digestate, a by-product of the anaerobic digestion of sugar beet pulp, with phosphorus, potassium, magnesium and boron can improve digestate performance as a soil amendment. The materials of this study were: digestate and sugar beet roots (Beta vulgaris cv. Fighter). A field trial was carried out on sugar beet growth under soil application conditions of solid and liquid digestate fractions with or without supplementation with P, K, Mg and B. It was shown that the root yield obtained from the plots amended with digestate supplemented with P, K, Mg and B was higher compared to the yield of other treatments. Soil amendment with digestate supplemented with P, K, Mg and B affected quality parameters of sugar beet roots. An increase in the following parameters under the effects of enriched digestate application was found: sucrose content, dry residue, pomace content, inverted sugars, α-amino and amide nitrogen fractions, as well as sodium and potassium content. A reduction in the content of conductometric ash was noted but this difference was not proven. The enrichment of digestate with P, K, Mg and B resulted in the beneficial modification of beet roots' processing parameters with the exception of the predicted content of sugar in molasses. In the case of the liquid fraction and its supplementation with P, K, Mg and B, six among eleven technological quality parameters were increased.

Keywords: sugar beet pulp digestion; digestate; supplementation of digestate; soil amendment; processing parameters of sugar beet

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1. Introduction

The anaerobic digestion of organic wastes is a process to acquire biomethane used for energy purposes. Today, this idea of turning crop residues into energy is widely accepted around the world [1–6].

In light of our earlier publications, the production of biogas from sugar beet pulp as well from other wastes generated during sucrose extraction in sugar beet processing plants is a profitable way to manage by-products [7–10].

The technology of biogas generation using agricultural residues and plant by-products has many economic (biogas production and energy gain) and environmental (reduction in the pollution load resulting from the elimination of fossil fuels) benefits and can be implemented in any country [7].

The very important environmental aspect of biogas production is the fact that anaerobic digestion installations generate large amounts of by-product called digestate. It is estimated that one gasifier of capacity of 1 MW(e) generates annually more than 30,000 Mg of digestate (fresh weight) [8]. In addition, this by-product can be treated as a valuable soil amendment because it can positively affect soil properties and is a source of available nutrients for crops. The enrichment of the soil habitat with organic matter and the promotion of microbial development are added values of digestate soil application [9]. There is an environmental concern connected with the risk of agricultural soil with heavy metals and persistent organic pollutants, and in the report [10] the model of monitoring sewage sludge can also be directly applied for digestate.

It should be mentioned that in the course of the anaerobic digestion of plant by-products, the decomposition of the labile fraction of organic matter is very pronounced, which finally results in the elimination of odor [11]. Therefore, in the chemical composition of digestate, stable organic compounds usually dominate, such as cellulose, lignin and complexes of lipids and steroids, which are precursors of humic substances. Organic compounds containing nitrogen and phosphorous can readily be decomposed and they are sources of plant-available ammonia and phosphate ions [12,13].

Therefore, digestate can be used as a relatively quick-acting soil amendment resembling more mineral fertilizers than organic amendments. Soil application is considered the most economic method of digestate management, which enables the recycling of organic and mineral compounds into agrobiocenoses [14,15]. This method of by-product utilization can limit greenhouse gas emissions. The other environmental benefit of digestate utilization is the limitation of the usage of mineral fertilizers as this results in saving non-renewable resources (phosphates and natural gas), which are important raw materials for the fertilizer industry [15]. In digestate, readily available forms of nutrients occur, and the best example is ammonia and therefore digestate directly affects crops growth [8,16]. Digestate also contains substantial amounts of organic substances that can increase the pool of organic carbon in the soil, which, in turn, positively affects the rate of microbial activity and improves the enzymatic properties of the soil [8,17–21]. Therefore, in long term digestate is able to regulate the rate of nutrient release from organic compounds. It is worth mentioning that digestate application improves soil texture and increases its ability to retain water and nutrients [22,23].

For technological reasons, in many installations digestate is separated into two fractions—solid and liquid [24]. Both fractions show different physical and chemical properties.

The separated solid fraction contains mainly structural organic compounds (mainly cellulose and lignin) and a high concentration of mineral compounds is found. Therefore, this substance is applied as a soil conditioner. Because of the relatively high content of dry matter, the solid fraction of digestate can be transported over long distances [25].

The liquid fraction usually contains a considerable concentration of ammonia nitrogen (ca. 18 kg $N\text{-}NH_4$ Mg^{-1} fresh weight) and potassium (ca. 9 kg K Mg^{-1} fresh weight) and a relatively low concentration of phosphorous (0.3 P Mg^{-1} fresh weight). The results of some studies [26–28] showed that the liquid fraction of digestate can be compared to nitrogen–potassium fertilizers and that this fraction can also be applied in sophisticated irrigation systems [29].

There are numerous reports from field and pot trials and the authors demonstrated the beneficial effects of digestate application to agricultural soil on crop yields [15,30–42]. It is outlined that the desirable effects of the agricultural utilization of digestate can be achieved, i.e., complete avoidance of fertilizers' usage due to the presence of easily available forms of the most important biogenic nutrients—nitrogen and phosphorous, which has a desirable environmental impact.

Furthermore, reports showing a lack of any crops' response to the soil application of digestate and very critical views of the suitability of by-products of anaerobic digestion can be found as well as concerns of the necessity of applying digestate bearing in mind the environmental safety of this practice [9,43,44].

It is worth mentioning that research concerning the utilization of digestate from sugar beet pulp and the application of this by-product in sugar beet plantations is very scarce. Furthermore, the authors could not find publications describing the application of digestate to crops that are stock materials for the food industry.

In our earlier manuscripts [45–48], some effective methods of applying sugar beet pulp digestate have been given. The idea presented there was to replace the rate of 120 kg N ha^{-1} in mineral fertilizers by an appropriate rate of digestate.

It is known that the application of mineral fertilizers using their appropriate rates in sugar beet plantations can support the maintenance of proper relations between all essential nutrients, which is impossible when digestate is meant to replace the application of all mineral fertilizers because digestate is not balanced due to its chemical composition. Inadequate levels of phosphorous, potassium, magnesium and boron compared to sugar beets' nutritional demands have been shown.

Therefore, in the 2017 growing season, different methods of fertilization of sugar beet plots with digestate were studied and included treatments with digestate supplemented with phosphorus, potassium, magnesium and boron to the optimal levels for sugar beets determined to obtain a high root yield. The aim of the studies carried out was to find out if such a supplementation could have better results for sugar beet production than the application of digestate without enrichment.

2. Material and Methods

Liquid and solid fractions of digestate collected from an industrial gasifier processing sugar beet pulp and sugar beets cv. Figher were the studied materials.

The solid fraction of the digestate studied contained: 9.34% nitrogen (N), 0.65% phosphorous (P), 3.13% potassium (K), 10.2% calcium (Ca), 0.845% magnesium (Mg), 7.1% sulfur (S), 0.008% boron (B), 8.1 mg Cu kg^{-1} copper and 24 mg Mn kg^{-1} manganese. However, the liquid fraction showed different patterns, including: 4.68% nitrogen (N), 0.456% phosphorous (P), 0.607% potassium (K), 4.77% calcium (Ca), 0.305% magnesium (Mg), 7.2% sulfur (S), 0.011% boron (B), 8.4 mg Cu kg^{-1} copper and 22 mg Mn kg^{-1} manganese.

Conventional complex fertilizers for the Polish market dedicated to sugar beets of the commercial name 'Lubofos for beets' were used in our previous experiment as a control. The composition of this fertilizer was as follows: 3.5% nitrogen (N), 4.4% phosphorus (P), 17.4% potassium (K), 4.3% calcium (Ca), 1.3% magnesium (Mg), 6.8% sulfur (S), 0.2% boron (B), 8.0 mg Cu kg^{-1} copper and 21 mg Mn kg^{-1} manganese. Under conditions of Polish agriculture to achieve high sugar beet yield, this fertilizer is used to apply the following rates of essential nutrients: 120 kg N, 133 kg, 50 kg P, 45 kg Mg, 70 kg Na and 40 kg S ha^{-1}.

When the above data are compared, it is clear that digestate is deficient in phosphorus, potassium, magnesium and boron in both fractions in relation to standard fertilizer. Therefore, two forms of digestate were studied, i.e., two fractions: solid and liquid ones without or with supplementation. As supplements, mineral fertilizers were applied: triple superphosphate (17.5% P), potassium salt (50% K), Supermag (20% Mg) and Solubor® DF (17.5% B).

The weather pattern in the season of the studies (2017) is presented below in Table 1. It should be mentioned that this year was characterized by an unintended pattern of precipitation and temperature distribution because the number of hours with direct sunlight in September was rather low, which was accompanied by a very high precipitation sum, which did not favor a high sugar accumulation in sugar beet roots.

Table 1. Weather conditions in growing season 2017.

Parameter	Apr	May	June	Jul	Aug	Sept	Oct	Nov
Daily temperature, °C	6.7	13.1	17.1	17.7	18.6	13.2	9.7	4.4
Number of hours with direct sunlight	146	252	256	231	250	125	93	49
Precipitation, mm·m^{-2}	58	56	129	61	54	185	89	46

The area of a single plot was 18.75 m^2 and the Latin square modified design was applied due to the extremely low soil variability at the Institute Experimental Centre. The forecrop was winter wheat. The experiment was carried out in triplicate.

The following experimental treatments were introduced, keeping the nitrogen rate at the same level, i.e., 120 kg N ha^{-1}:

Solid fraction of digestate;

Solid fraction of digestate supplemented with phosphorus, potassium, magnesium and boron at rates equivalent to the standard rate of complex fertilizer;

Liquid fraction of digestate;

Liquid fraction of digestate supplemented with phosphorus, potassium, magnesium, and boron at rates equivalent to the standard rate of complex fertilizer.

The laboratory methods applied in analyses of stock material and technological parameters have been described in detail in our earlier publication [47].

3. Results and Discussion

3.1. Suitability of by-Products of Anaerobic Digestion as a Soil Amendment for Sugar Beet Field

The characteristics of studied fractions of digestate obtained from the processing of sugar beet pulp and applied to experimental plots are given in Table 2 on the background responsible permissible levels given by the Polish Ministry of Agriculture and Rural Development.

Table 2. Characteristics of digestate fractions studied in light of the permissible levels given by the Ministry of Agriculture and Rural Development of Poland.

Parameter	Units	Fraction of Digestate:		Permissible Level for Soil Application in Crop Production
		Solid	Liquid	
pH	pH-H_2O	7.7	7.6	–
Dry matter	% fresh weight	20.1	4.0	–
Organic substances	% fresh weight	68.6	76.8	–
Cadmium (Cd)	mg·kg DM^{-1}	1.23	1.35	≤20
Chromium (Cr)	mg·kg DM^{-1}	<25	<25	≤750
Copper (Cu)	mg·kg DM^{-1}	8.10	8.40	≤300
Nickel (Ni)	mg·kg DM^{-1}	8.35	7.40	≤500
Lead (Pb)	mg·kg DM^{-1}	<5.0	<5.0	≤16
Zinc (Zn)	mg·kg DM^{-1}	250	320	≤1000
Mercury (Hg)	mg·kg DM^{-1}	0.066	<0.050	≤2.5
Manganese (Mn)	mg·kg DM^{-1}	24	22	–
Sulfur (S)	% DM	7.1	7.2	–
Calcium (Ca)	% DM	10.2	4.77	–
Magnesium (Mg)	% DM	0.845	0.305	–
Total nitrogen Kjeldahl's (N)	% DM	9.34	4.68	–
Total phosphorous (P)	% DM	0.650	0.456	–
Potassium (K)	% DM	3.13	0.607	–
Boron (B)	% DM	0.008	0.011	–
Salmonella bacteria	cfu in 100 g	not present	not present	0
Living eggs of parasites Atrichuris sp., Trichuris sp., Toxocara sp.	number in 1 kg DM^{-1}	not present	not present	0

Both studied fractions have been listed in the national waste catalogue: liquid fraction at the number of 09 06 05—liquids from anaerobic digestion of animal and plant wastes—and solid fraction at the number of 09 06 06—stabilized waste from anaerobic digestion of animal and plant wastes.

The presented results show that the studied fractions of digestate obtained from the anaerobic digestion of sugar beet pulp contain considerable amounts of essential nutrients, i.e., nitrogen, potassium and phosphorous, but what is of high importance from an environmental point of view is that levels of trace metals are low and therefore safe. Generally, the solid fraction was more abundant in all studied elements (with the exemption of zinc only). It should be added that the studied by-products can be treated as a source of organic substances, which are very important from agricultural aspects.

Two digestate fractions were safe because no Salmonella or parasites were isolated.

Therefore, it can be stated that the studied by-products of the anaerobic digestion of sugar beet pulp were abundant in macro and micronutrients for plants as well as environmentally and sanitarily safe.

3.2. The Effects of Studied Digestate Fractions on Sugar Beet Growth and Yield

In Figures 1 and 2, the results of the statistical analysis of the weight of single sugar beet plants are presented.

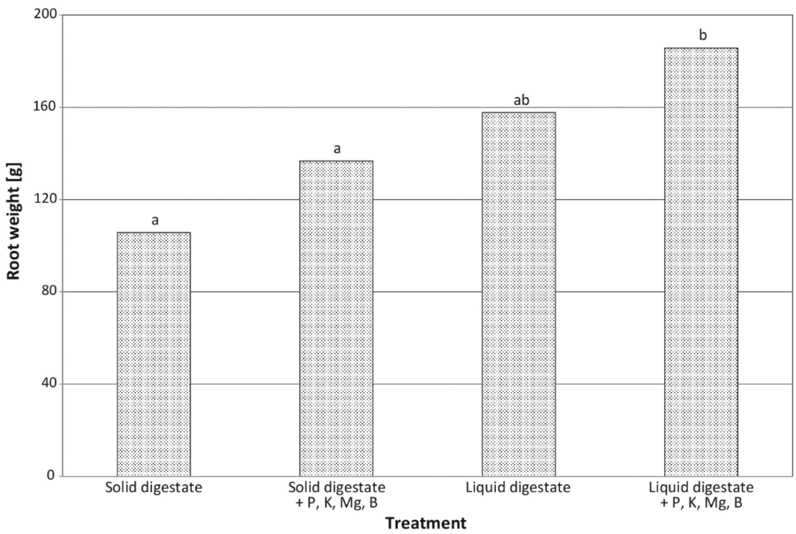

Figure 1. Weight of sugar beet root at harvest in relation to soil amendment applied. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

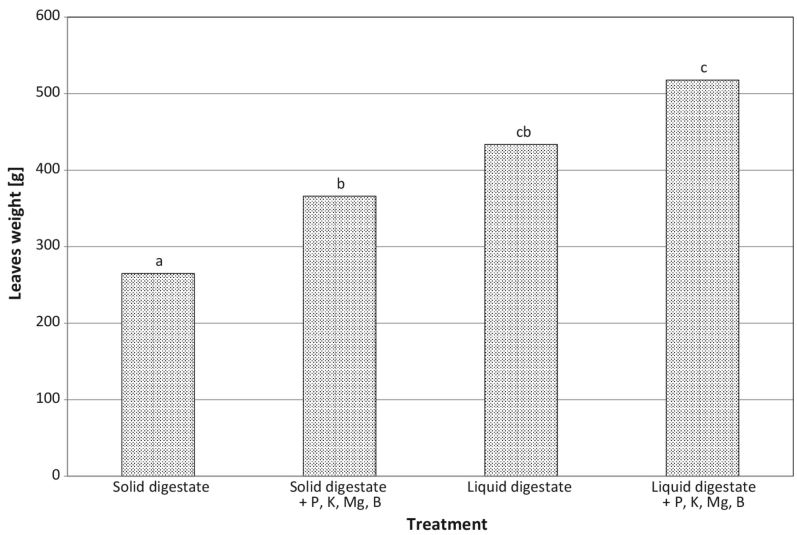

Figure 2. Weight of sugar beet leaves at harvest in relation to the soil amendment applied. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

The supplementation of both digestate fractions studied (solid and liquid) with P, K, Mg and B resulted in an increase in the weight of the root and leaves of sugar beets grown on experimental plots. The supplementation of solid and liquid fractions of digestate resulted in a 23% and 15% increase in single root weight, respectively. A similar trend was found for the effect of digestate supplementation on sugar beet leaf weight.

It should be noted that the mentioned differences were statistically proven.

3.3. The Effects of Digestate Fractions Studied on the Quality of Sugar Beets as a Stock Material

The results of a detailed analysis of the sugar beets harvested as stock material for sugar processing plants are given in Table 3.

Table 3. Results of soil amendment with by-products of anaerobic digestion on the chemical quality of the stock material for processing.

Treatment	Parameter (%)								
	Sucrose	Dry Residues	Poma-ce	Inverted Sugar	α-amino Acid N	Amide N	ash	Na	K
Solid fraction of digestate	13.5 [a]	18.6 [ab]	3.4 [ab]	0.04 [a]	0.003 [ab]	0.014 [ab]	0.60	0.021 [a]	0.150 [a]
Solid fraction of digestate + P, K, Mg and B	13.9 [a]	19.9 [b]	3.5 [ab]	0.08 [b]	0.007 [c]	0.016 [b]	0.54	0.036 [b]	0.173 [ab]
Liquid fraction of digestate	13.9 [a]	18.4 [ab]	3.5 [ab]	0.04 [a]	0.005 [b]	0.013 [ab]	0.58	0.033 [ab]	0.145 [a]
Liquid fraction of digestate + P, K, Mg and B	14.9 [b]	19.3 [b]	3.6 [b]	0.06 [ab]	0.007 [c]	0.014 [ab]	0.48	0.042 [b]	0.152 [a]

Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

As it can be concluded from the results presented in Table 3, the supplementation of digestate with P, K, Mg and B significantly affected most of the studied parameters of the chemical quality of sugar beet roots as a stock material for processing.

An increase in important parameters such as sucrose, pomace, dry residue, inverted sugar and amide and α-amino acid nitrogen species was found, as well as sodium and potassium content, under the effects of digestate supplementation for solid and liquid fractions. The ash content was reduced, but this effect was not significant.

The most important index, i.e., sucrose concentration, ranged from 13.5 to 14.9%, which can be estimated as rather low values (under climatic conditions in Poland, it ranges from 14 to 20%), which was mainly due to prevailing weather conditions during the growing season.

A significant increase in sucrose concentration in sugar beet roots was found only in the case of treatment with the supplementation of the liquid fraction compared to other experimental treatments.

As can be seen in Table 3, the content of dry residues was relatively low because usually it is at a level of 25%. In reported studies, a level of 19% of dry residues was observed only for treatments with the application of both supplemented digestate fractions.

The pomace content in sugar beets of good processing quality should be 4–5%. Therefore, it is obvious that the values obtained in our studies are very low and the variability of the results was also limited.

Inverted sugars in normal agricultural conditions occur at the level of 0.1–0.2%. This parameter in our studies showed a very low level and the highest 0.08% was found for treatment with the solid fraction of digestate supplemented with P, K, Mg and B.

Both tested nitrogen species present in sugar beet roots, i.e., amide and α-amino nitrogen, are harmful to processing in the factory. Amino acids negatively affect the reaction of juice, and they form colored products with molecules of simple sugars. Additionally, during the high-temperature stage of sugar processing, amino acids form gaseous ammonia, which pollutes condensate that enters the steam oven. As it can be seen in Table 3, the content of α-amino nitrogen ranged from 0.003 to 0.007%, and the lowest value was found for the treatment of the solid fraction of digestate without supplementation. The concentration of amide nitrogen ranged at very low limits, that is, 0.012–0.016%. In light of the results presented, it can be concluded that both concentrations of harmful nitrogen species were low and therefore could not interfere with the processing of sugar beets.

The presence of soluble ash (sodium and potassium) in sugar beet tissues is positive in terms of maintaining the alkalic reaction of juices throughout the process in the sugar beet factory. On the other hand, sodium and potassium ions show a high affinity for sucrose molecules, which results in a high sugar content in molasses, and the final effect is a lower effectiveness of sugar beet processing in the factory. Analyses of results in Table 3 showed that experimental treatments did not affect the content of soluble ash.

The ranges of variability of sodium and potassium were 0.021–0.042% and 0.145–0.173%, respectively (Table 3). It can be stated that only sodium content significantly increased for the treatment of the solid digestate fraction with supplementation, and differences in potassium concentration in sugar beet tissues were within experimental errors.

3.4. Determination of the Effects of Soil Application of Digestate on Technological Quality of Stock Material

The experimental results from Table 3 were further processed to calculate the estimation of parameters important for processing roots in the sugar factory.

The results of calculations were subjected to analysis of variance and are presented in Figures 3–13 together with optimal values for given parameters.

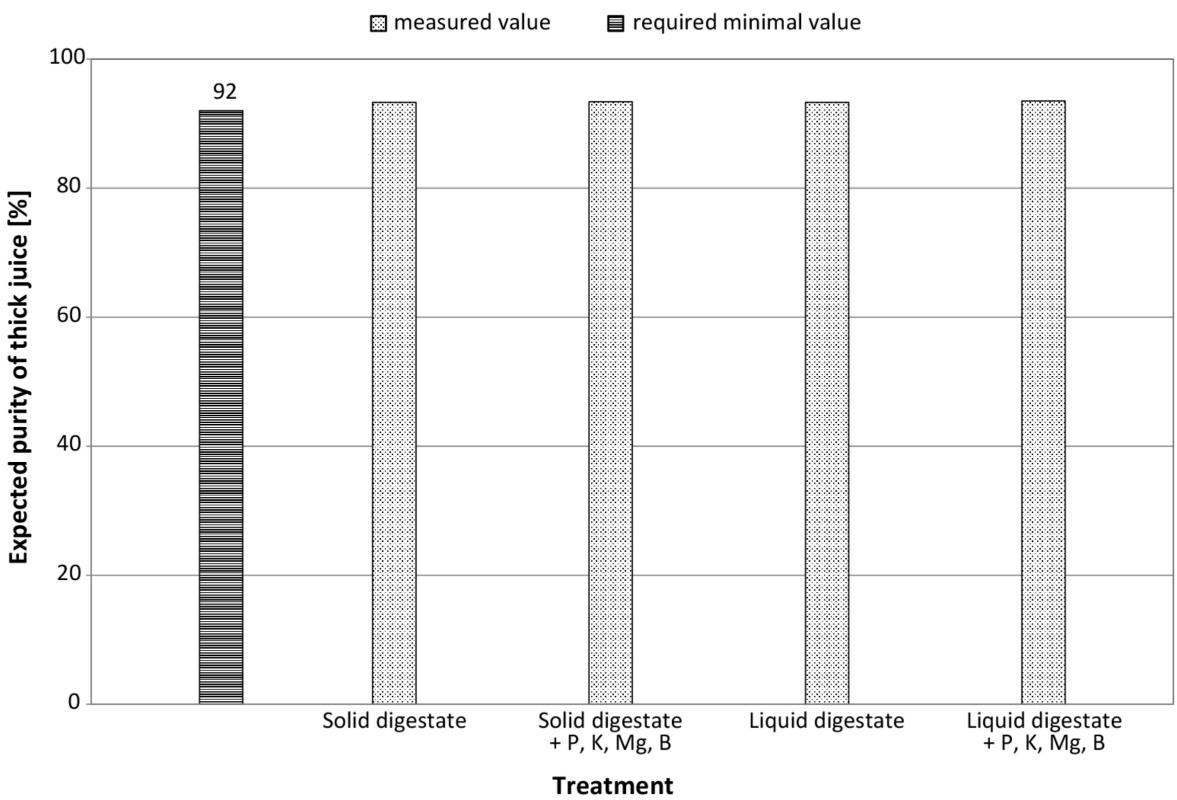

Figure 3. Expected purity of thick juice in relation to experimental treatments.

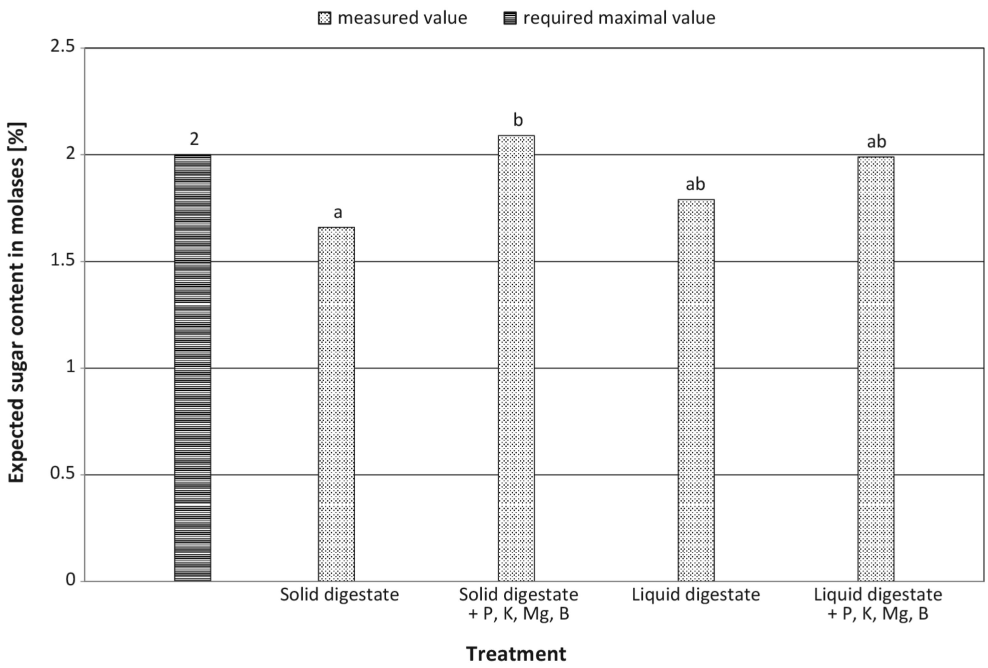

Figure 4. Predicted content of sugar in molasses in relation to experimental treatments. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

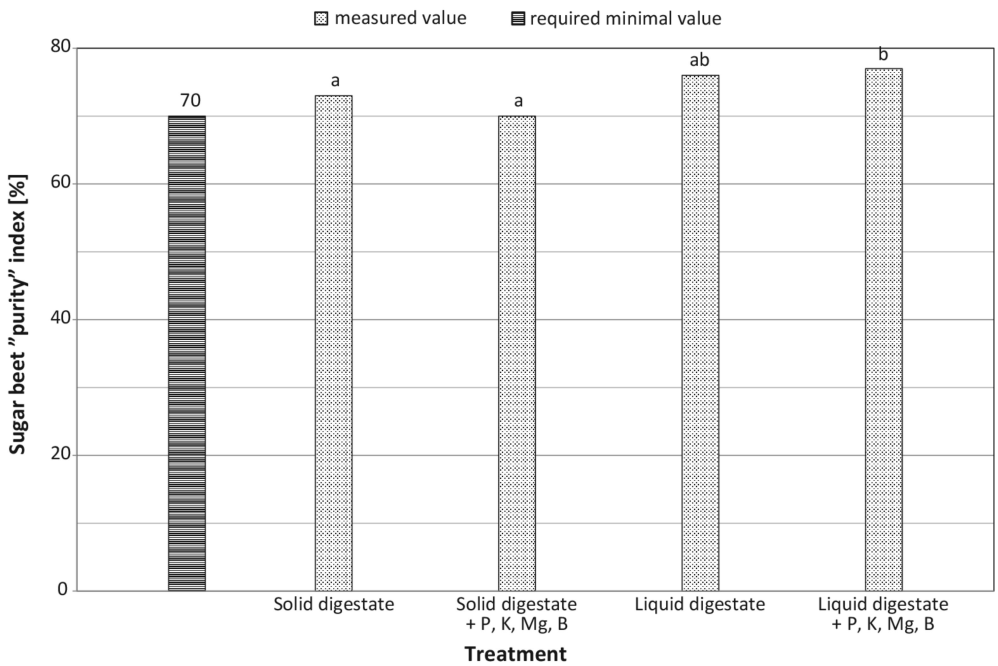

Figure 5. Index of sugar beet "purity" in relation to experimental treatments. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

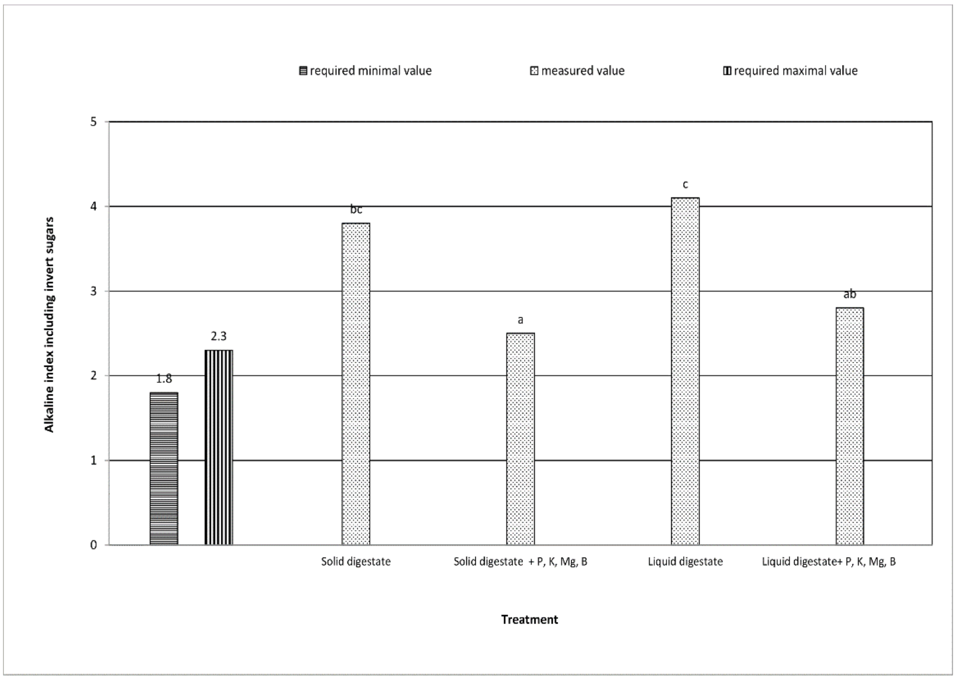

Figure 6. Alkaline index including inverted sugars in relation to experimental treatments. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

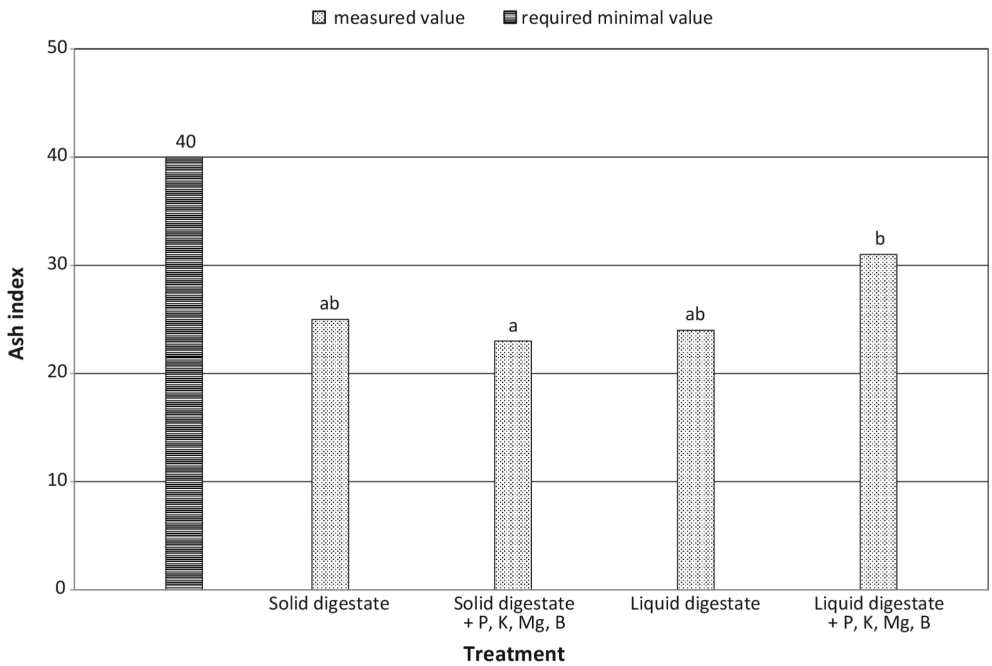

Figure 7. Ash index in relation to experimental treatments. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

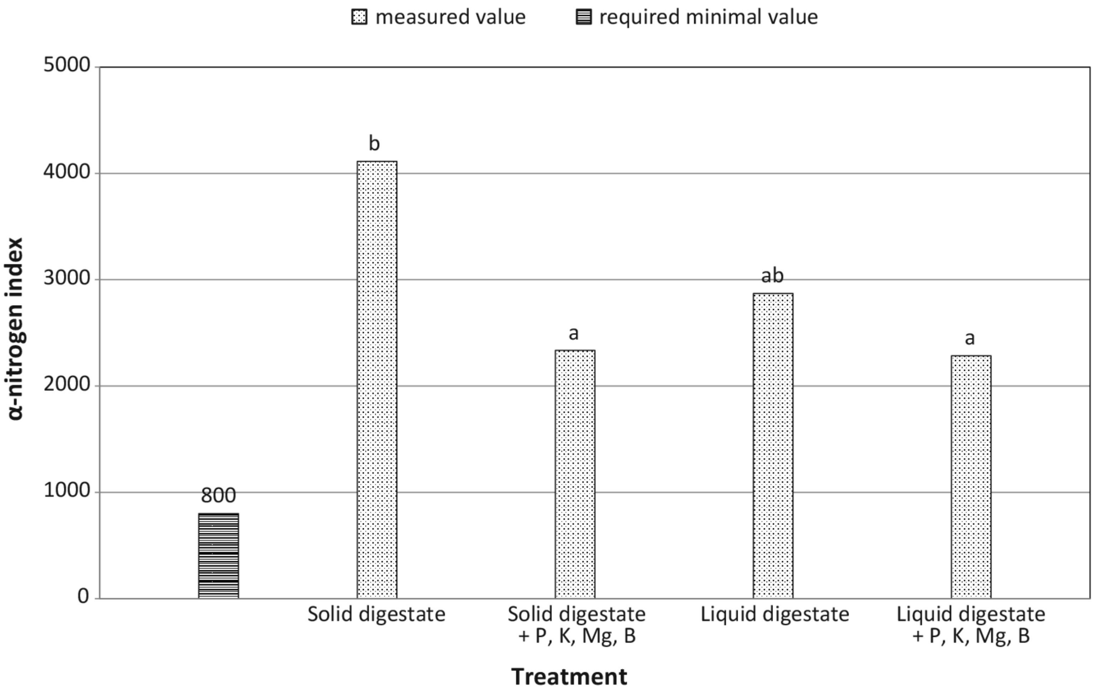

Figure 8. Index of α-amino nitrogen in relation to experimental treatments. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

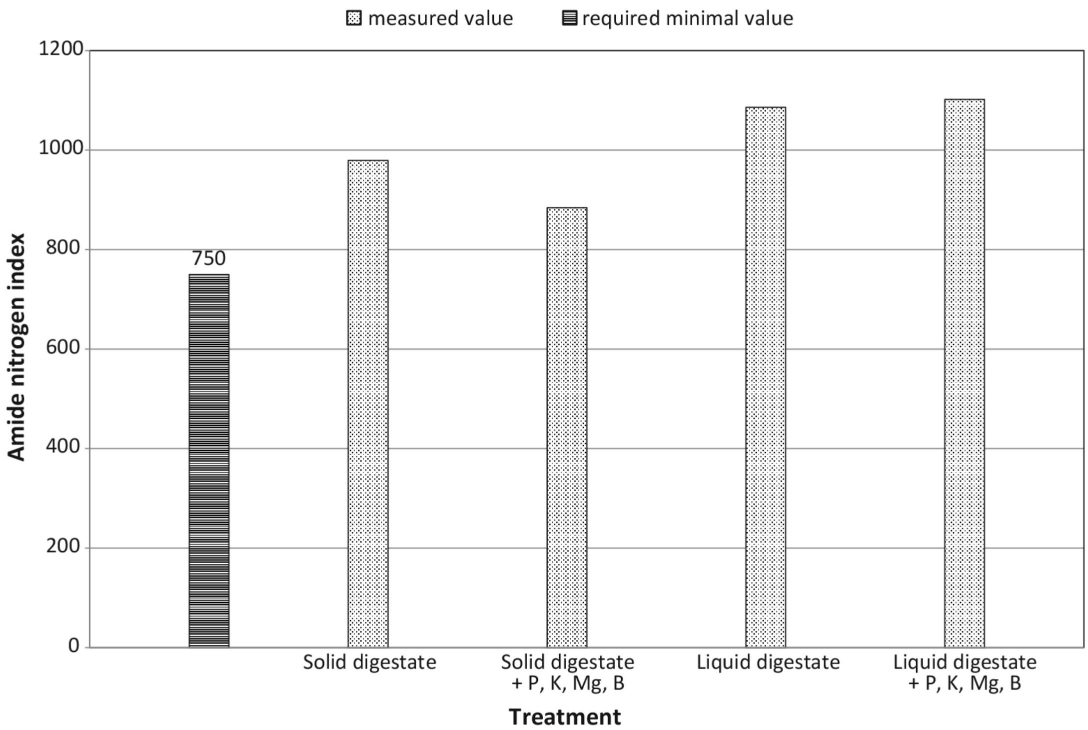

Figure 9. Index of amide nitrogen in relation to experimental treatments.

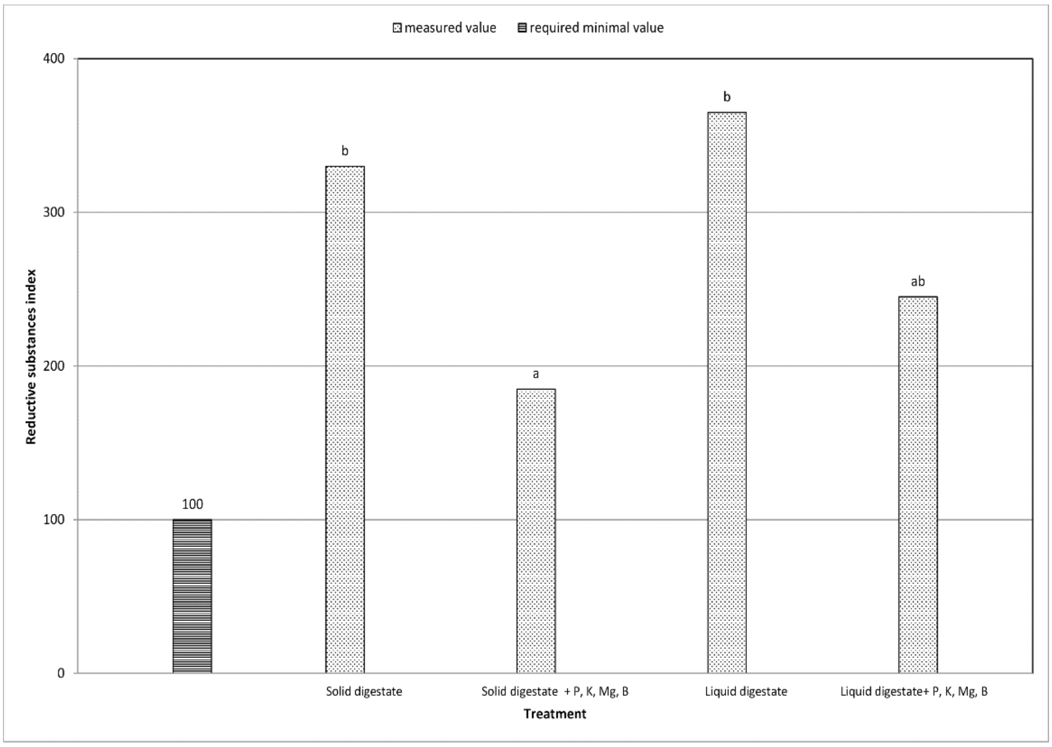

Figure 10. Index of reductive substances in relation to experimental treatments.

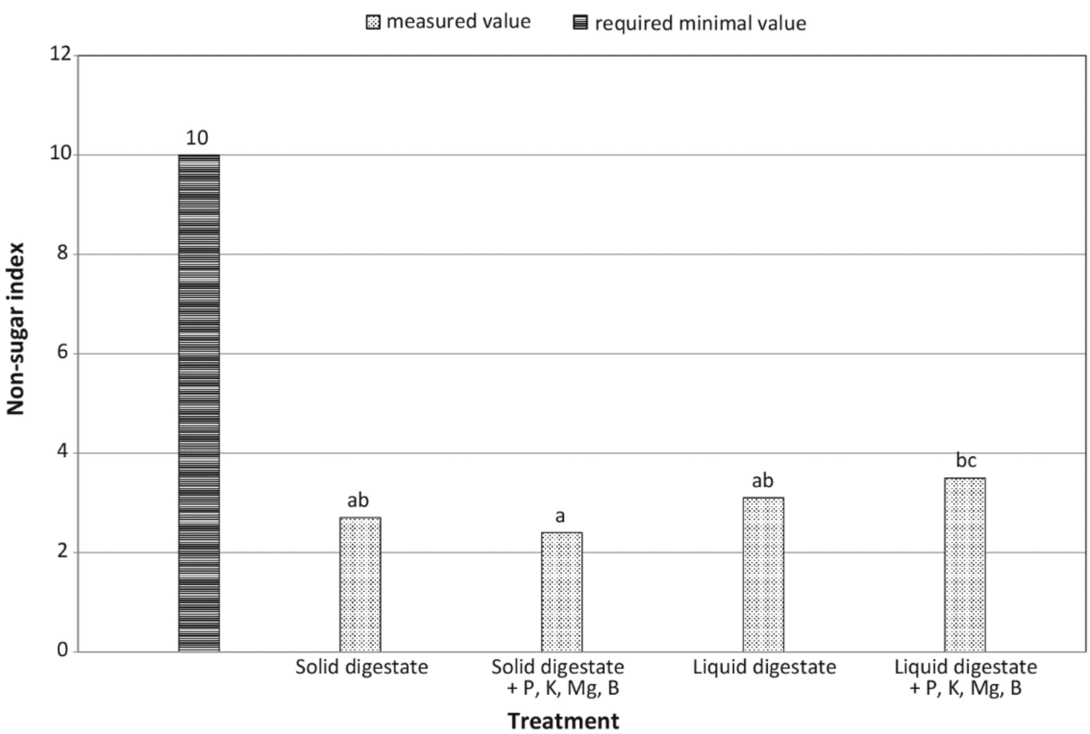

Figure 11. Index of non-sugar substances in relation to experimental treatments. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

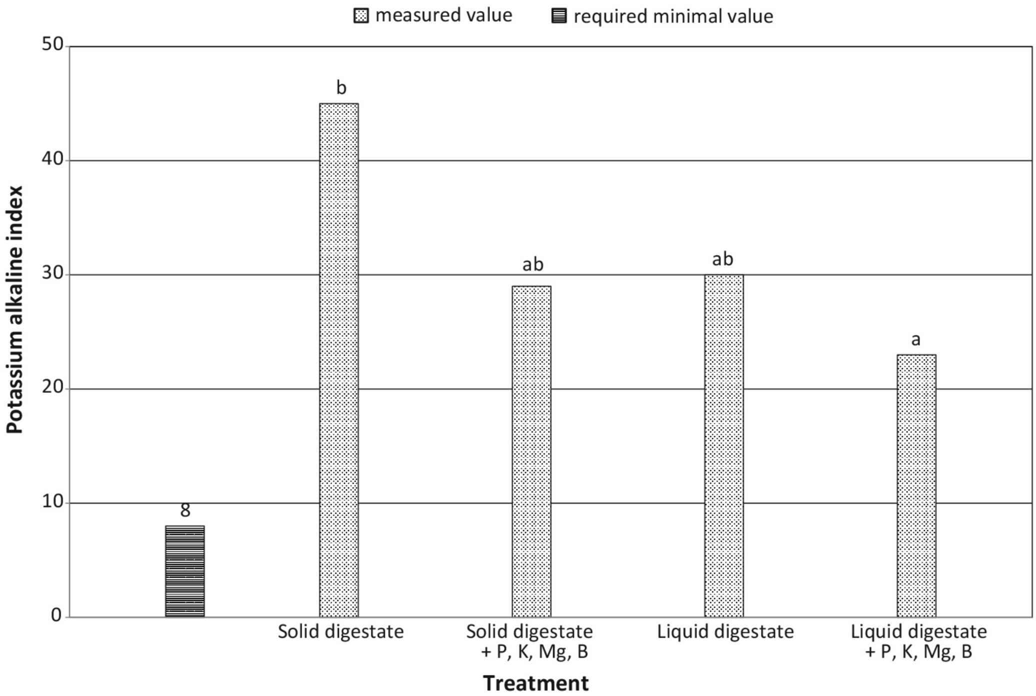

Figure 12. Index of potassium alkalinity in relation to experimental treatments. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

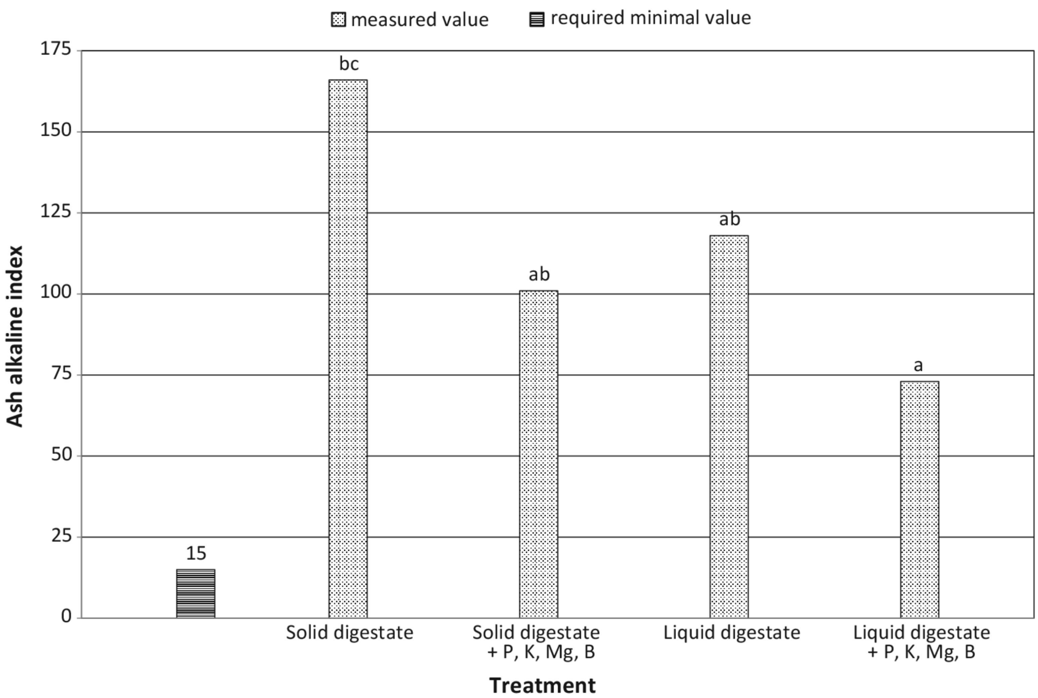

Figure 13. Index of ash alkalinity in relation to experimental treatments. Analysis of variance was performed in the design of a factorial experiment and to estimate the significance of differences using Fisher's test of homogeneity groups ($p \leq 0.05$), and the following symbols of homogeneity were used in the figures: Different letters—different groups; the same letter—the same homogeneity group; no letter—lack of statistical differences (that is, all values in the same homogeneity group).

The supplementation of both digestate fractions (solid and liquid) used as soil amendments with P, K, Mg and B resulted in an increase in the predicted purity of the thick juice, but differences could not be proven. What is very important is the fact that, for all treatments, values higher than the optimal level were recorded (Figure 3).

It was found that the supplementation of digestate with P, K, Mg and B was reflected by an increase in the predicted content of sugar in molasses. In the case of the supplementation of the liquid fraction, this increase by 20.6% appeared to be significant, and when the solid fraction digestate was enriched with P, K, Mg and B an increase of 11.1% appeared to be insignificant. It is worth mentioning that losses of sucrose in molasses are the dominant part of total sugar losses during sugar beet processing in the sugar plant. Generally, the level of 2% sugar content in molasses is recognized as an acceptable level of losses. From Figure 4, it can be seen that a higher value than 5% was found for treatment with the solid fraction of digestate supplemented with P, K, Mg and B, and in the case of other studied treatments the level of 2% was not exceeded.

The supplementation of the solid digestate fraction with P, K, Mg and B caused a significant reduction in the "purity" of sugar beet by 4.1%. For treatment with the supplementation of the liquid fraction, an insignificant increase by 1.3% was found. The "purity" index of sugar beets at the level of 70% is recognized as beneficial for processing purposes. It should be noted that the value of this parameter in our studies was exceeded at a level of 70% for all treatments studied; however, the supplementation of the solid digestate fractions with P, K, Mg and B resulted in a reduction in this parameter, but an optimal value was maintained (Figure 5).

It was found that the alkaline index including inverted sugars under the effect of the supplementation of digestate with P, K, Mg and B was reduced, which is beneficial for processing irrespective of the fraction of digestate applied (by 34.2 and 31.7% for solid and liquid fraction, respectively). This specific index shows if the appropriate alkalinity of juices could be maintained because this limits sucrose losses in molasses. The optimal value of this index ranges from 1.8 to 2.3. As can be concluded from the data shown in Figure 6, the range of this index was between 2.4 and 4.1. Under conditions of sugar processing, the plant acidification of juices could be necessary, and only in the case of treatment with the supplemented solid fraction of digestate was the optimal value of this index found (Figure 6). The significance of alkalinity, or sometimes called alkalinity reserve for the course of sugar extraction, was underlined, and this parameter is pointed out as a crucial one for the technological quality of sugar beets [49].

From the data included in Figure 7, it can be noted that the value of the ash index under the effect of the supplementation of digestate with P, K, Mg and B was reduced for the solid fraction (by 8%) and increased for the liquid fraction (by 22.5%). All mentioned differences were insignificant. All studied samples of sugar beet roots were beneficial for the processing value of the ash index, i.e., lower than the threshold of 40, because all registered values ranged from 25–31.

The supplementation of digestate with P, K, Mg and B for both studied fractions resulted in a significant decrease in the α-amino nitrogen index (by 43.3 and 20.4% for solid and liquid fraction, respectively). All sugar beet root samples studied showed favorable values of this index, i.e., >800. The average values of this index ranged from 2285 to 4114, which indicates that no problems would occur with the formation of colorful by-products and the reduction in the pH of juices (Figure 8). It was reported that so-called "impurities", and among them particularly nitrogen compounds, are responsible for sugar losses in molasses and therefore they should be routinely determined in sugar beets [50,51].

The value of the index of amide nitrogen was modified by the supplementation of soil-applied digestate with P, K, Mg and B (Figure 9). In the case of the solid fraction, some reduction was found and a small increase for the supplementation of the liquid fraction was noted. However, the significance of the mentioned differences was not proven and all samples showed good values of the amide nitrogen index in the sugar beet processing aspect, i.e., higher than 750.

It was found that the supplementation of both studied digestate fractions with P, K, Mg and B resulted in a significant decline in the value of the index of reductive substances (by 43.9 and 32.9% for solid and liquid fraction, respectively). For all treatments studied, the values were higher than the minimal threshold, i.e., 100. It can be concluded that problems with colorful compounds and the pH of juices should not occur during sugar beet root processing in the factory (Figure 10).

Generally, values of the index of non-sugar substances in our studies appeared to be negative for processing, and under the effect of the supplementation of both studied digestate fractions with P, K, Mg and B, a reduction (by 11.1% for solid fraction) and an increase (by 11.4% for liquid fraction) were found (Figure 11). The range of this value was between 2.4 and 3.5, with a minimal threshold value of 10. The following problems during the processing of sugar beet roots from the field trial could be expected: the formation of colorful by-products, the accumulation of non-sugar substances in molasses and the modification of the pH of juices.

Under the effect of the supplementation of both studied digestate fractions with P, K, Mg and B, a reduction in the value of the index of potassium alkalinity was observed (35.6 and 23.3 for solid and liquid fraction, respectively). A minimum threshold value of 8 is recognized. As can be seen in Figure 12 for all experimental treatments, values higher than the minimal value were registered and ranged from 23 to 45.

All sugar beet samples studied showed favorable values of the index of ash alkalinity compared to the minimal value set at 15. The supplementation of both studied digestate fractions with P, K, Mg and B resulted similarly as to the index of potassium alkalinity to its reduction. For both fractions, this decrease was significant, and the range of the index of ash alkalinity ranged from 73 to 166.

4. Conclusions

A short summary of the effects of the supplementation of both digestate fractions studied with P, K, Mg and B is presented in Table 4. It is worth pointing out that the supplementation of the solid digestate fraction was effective because beneficial impacts of almost all technological parameters were found, with the exemption of only the expected content of sugar in molasses. However, in the case of the enrichment of the solid digestate fraction among eleven studied parameters, beneficial effects were found for six of them.

Table 4. Summary of the parameters' modification studied under effect of digestate supplementation with P, K, Mg and B.

Parameter	Modification of Parameters under Effect of Supplementation with P, K, Mg and B		Technological Effects of Modification of Digestate with P, K, Mg and B		Significance of the Difference between Treatments with and Without Supplementation with P, K, Mg and B	
	Liquid Fraction	Solid Fraction	Liquid Fraction	Solid Fraction	Liquid Fraction	Solid Fraction
Expected purity of thick juice (%)	increase by 0.1%	increase by 0.2%	+	+	ns	ns
Expected concentration of sugar in molasses (%)	increase by 20.6%	increase by 11.1%	–	–	**	ns
"Purity" of stock material (%)	decrease by 4.1%	increase by 1.3%	+	–	**	ns
Alkaline coefficient including inverted sugars	decrease by 34.2%	decrease by 31.7%	+	+	**	**
Ash coefficient	decrease by 8.0%	increase by 22.5%	+	–	**	**
α-amino acid coefficient	decrease by 43.3%	decrease by 20.4%	+	+	**	**
Amide nitrogen coefficient	decrease by 9.7%	increase by 1.5%	+	–	ns	ns
Coefficient of reductive substances	decrease by 43.9%	decrease by 32.9%	+	+	**	**
Non-sugar coefficient	decrease by 11.1%	increase by 11.4%	+	–	**	**
Alkaline potassium coefficient	decrease by 35.6%	decrease by 23.3%	+	+	**	**
Alkaline ash coefficient	decrease by 39.2%	decrease by 38.1%	+	+	**	**

Legend: +—beneficial effect; –—neutral or beneficial effect; ns—not significant; **—significant at $p < 0.05$.

Therefore, in light of our results obtained in the sugar beet growing experiment, it can be concluded that the supplementation of digestate fractions with P, K, Mg and B can improve the performance of this by-product used as a soil amendment.

The rapid development of the biogas sector in Poland and other countries in the EU makes further studies on digestate management necessary. We will develop our studies to find out if the application of digestate can bring not only environmental and agricultural benefits, but if it could be economically feasible.

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