Pol. J. Environ. Stud. Vol. 33, No. 2 (2024), 1215-1223
DOI: *10.15244/pjoes/172049* ONLINE PUBLICATION DATE: 2023-11-27

Original Research

The Reaction of Maize and Sorghum to Fertilization with Granulated Fertilizer Obtained from Digestate

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Received: 21 February 2023
Accepted: 8 September 2023

Abstract

The aim of the conducted observations was to examine the effect of fertiliser produced based on plant digestate and resulting from the process of anaerobic fermentation of a substrate with sorghum (20%), beet (60%), rye (10%) and grass (10%) on the growth and yield of sorghum and corn. A strict, single-factor pot experiment was carried out in 2017–2018 in the Swojec Agricultural Experimental Unit at the University of Life Sciences in Wrocław. Fertilisation with digestate was the tested factor, with a focus on its influence on selected energy plants. Sucrosorgo sorghum and Atletico maize were analysed. During the research, the pots were placed in a vegetation hall. The research proved that the use of digestate-based fertiliser improves the productivity of both sorghum and maize, but only with an additional dose of basic macronutrients. The optimal variant is a fertiliser dose of 20 g enriched with 1.0 NPK. Increasing the dose to 30 g and 1.5 NPK generally did not result in a significant increase in plant height or in fresh and dry weights.

Keywords: granulated fertilizer, digestate, maize, sorghum

Introduction

Post-fermentation pulp, which is the by-product of biogas production, can be used inter alia for fertilisation purposes in agriculture [1-6]. However, the fertilisation characteristics of the digestate vary. They depend on the substrates used, which may be as follows: plant biomass, waste from the agri-food industry or natural fertilisers [2].

According to legal regulations, a given digestate can be directly regarded as a fertiliser, a soil conditioner, or one of the raw materials to produce a fertiliser or plant conditioner [6, 7]. The best plant substrates used for biogas production are sugar beet, maize [8, 9], sorghum [10], and other grasses and cereals [11]. In addition, there are reports of other alternative

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plants that could be used for biogas production, including cup plants and willow-leaf sunflower [12]. The reason for selecting such a group of plants is that they are characterised by quite high biogas efficiency.

Furthermore, plant digestate can be used in the so-called closed cycle, as well as in accordance with the rules of the bioeconomy. In both cases, everything is based on the C2C [cradle-to-cradle] model [6, 13]. According to some reports [1, 5, 13-16], plant-derived digestate is an alternative to mineral fertilisers. Baryga et al. [1] demonstrated that the fertilisation of maize with pure digestate from beet pulp had a significant effect on cob yield compared to maize fertilisation with mineral fertiliser. Głowacka et al. [5], where the digestate substrates were corn silage (70%), sugar bagasse beet (15%), fruit pomace (5%), waste from dairy (5%) and manure (5%), proved its significant impact on the yield of *Panicum virgatum* L. and improved soil properties through reduced acidification, improved sorption properties, and increased its organic matter content and macroelement abundance. Plant digestate obtained from maize, as shown by Nabel et al. [15], can be used in soils with low soil water capacity (WHC), where the nitrogen supplied from the digestate was not immediately available for plants, thus creating a reservoir for plants.

However, Maucieri et al. [17] obtained the highest maize yield after the application of mineral fertilisation and 50% compost (regardless of the type of compost: (a) compost derived from green cuttings and depuration sludge (G+S), (b) from green cuttings, organic fraction of municipal wastes, and other organic materials (G+F+O), (c) from green cuttings (G), and (d) from green cuttings and organic fraction of municipal wastes (G+F) +50% mineral fertilisation treatments. The authors suggested that the organic form of N is less mobile than the nitric form. In addition, the authors of [17] concluded that under 100% compost fertilisation, the crops did not take up a large amount of N, but it did not generate an increase of NO_3-N leaching in the percolation water.

According to Muhammad et al. [18], combining organic and mineral fertilisation is the best option due to lower costs and lower environmental risks. The authors showed that cultivars of maize performed significantly better when N was applied as either Seed cake (SC)/ Poultry manure (PM) with urea at 25:75, SC and PM with urea at 25:25:50, SC/PrM (Press mud) with urea at 50:50, or all organic N sources (25%) with urea (75%), which was at par to 100% sole urea in all tested traits. As the authors showed, the reason for the higher grain yield of maize receiving both organic and mineral N in different proportions may be due to the improvement in soil water content, more nutrient availability, and more microbial activities. Radwan et al. [19] indicated that the combined use of organic and inorganic N increased N uptake by crops. Such a fertilisation system may provide a balance between micro- and macronutrients. It can also enhance the availability of plant nutrients, which would help to enhance the metabolic activity of microorganisms and improve plant growth [19].

The aim of the conducted observations was to examine the effect of fertiliser produced based on plant digestate and resulting from the process of anaerobic fermentation of a substrate based on sorghum (20%), beet (60%), rye (10%), and grass (10%) on the growth and yield of sorghum and corn.

Material and Methods

A strict, single-factor pot experiment was carried out in 2017-2018 in the Swojec Agricultural Experimental Unit belonging to the University of Life Sciences in Wrocław.

Fertilization with digestate was the tested factor, with focus on its influence on selected energy plants – Sucrosorgo sorghum and Atletico maize were analyzed. During the research, the pots were placed in a vegetation hall.

Digestate

The digestate used in the experiment came from a biogas laboratory after the process of anaerobic fermentation of a substrate based on sorghum (20%), beet (60%), rye (10%), and grass (10%). Granular fertilizer was produced with the following content: N 5% TS, P 9% TS, and K 12% TS so in 1 ton of fertilizer there would be 50 kg N, 90 kg P and 120 kg K [20]. Various fertilization variants were used in the experiment (Table 1); each test site had 5 replications.

Soil Conditions

The soil used for the experiment was river mud consisting of strong clay sand and lined with weak sand – quality class IV b. The experiment had an irrigation system maintaining constant soil moisture at the level of 65% capillary water capacity. Before setting up the experiment, the soil was subjected to chemical analysis (Table 2).

Table 1. Scheme of fertilization treatment and abbreviations.

Site	Abbreviation
Control	Contr.
Digestate (clean) dose 20 g	D20
Digestate dose 10 g + enriched with 0.5 NPK	D10-0.5 NPK
Digestate dose 20 g + enriched with 1.0 NPK	D20-1 NPK
Digestate dose 30 g + enriched with 1.5 NPK	D30-1.5 NPK
NPK (carbamide 46%-0.2 g (N), Superphosphate 40%-2.0 g (P), Potassium salt 60%-1.0 g (K)	NPK

Table 2. Soil parameters.

N g/kg	P mg/kg	K mg/kg	Mg mg/kg	Ca mg/kg	C%	Ug TF/g*h	Zn mg/kg	Mn mg/kg	Ni mg/kg	pH
0,5	102	135	73.8	544	0.79	0.43	15.48	125.5	1.95	6.3

Table 3. The list of performed agrotechnical treatments.

Plant	Agrotechnical sowing period		Sowing depth	Harvest period	
	2017	2018	[cm]	2017	2018
Sorgo Sucrosorgo	1 VI	1 VI	5–7	12.10	8.10
Maize – Atletico K 280	1 V	1 V	5–7	16.08	16.08

Plant Studies

During the growing season, the growth dynamics of maize and sorghum plants was assessed (plant height measurement every two weeks from the 2nd decade of April to the end of the 1st decade of October). Moreover, the content of chlorophyll was determined (measured at 2-week intervals from the 2nd decade of April to the end of the 1st decade of November). Measurements were taken with a CCM-200 chlorophyll meter (Opti-Sciences, Tyngsboro, MA, USA). Soil respiration was measured after the plants have been cut with use of an EGM-4 infrared gas analyzer equipped with SRC-1 soil respiration chamber (PP systems, Hitchin, UK). In the experiment, the yield of fresh plant weight (fresh weight of leaves and stems) and dry weight were also assessed. Additionally, fresh weight and number of cobs were determined for maize. The list of performed agrotechnical treatments are displayed in Table 3.

Chemical Analysis of Plant Material – Straw of Corn and Sorghum

For chemical analysis, corn and sorghum straw was used. Total nitrogen was determined via the Kjeldahl method, using Büchi Distillation Unit K-355 (recovery rate ≥99.5%, reproducibility (RSD) ≤1%, detection limit ≥0.1 mg nitrogen). Total potassium was determined via flame photometry using BWB XP flame photometers (BWB Technologies) (Specificity /K/ = <1% to each other when equal in concentration at <100 ppm), limit of detection (LOD K – 0.02 ppm) and limit of quantification (LOQ K – 0.05 ppm), and total phosphorus via the colorimetric method using SPEKOL 11 spectrophotometer.

Weather Conditions

The temperature during the experiment was characterized by higher values both in the first and second year of the study compared to the multi-year period (Fig. 1). During sowing month, the difference in temperature between the second year of the experiment and the multi-year period was 5.1ºC. In addition, throughout the growing season in the second year of observation, several degrees temperature differences were noted compared to multi-year periods. The difference between the data in May was 3.1ºC, in June 2.4ºC, in July 1.8ºC and in August 3.3ºC In the first year of the experiment, differences in temperature were also noted, but they were significantly smaller, maintaining a difference of up to 2ºC.

Statistical Analyses

The analysis of variance (ANOVA) was done at the significance level $p<0.05$ using Statistica program 13.1 (StatSoft, Kraków, Poland) and AnalVar. 5.3 software (acc. to Franciszek Rudnicki). The experiment included two factors: two years, six types of fertilizers, and five randomized replicates. For the resulting data presented in the figures, standard deviations (SD) were calculated.

Results

The effect of applied fertilisation on plant height was already clear in the initial stages of development (Fig. 2). As time passed and the plant grew, this effect became even more significant. The highest increase was recorded after the use of digestate in the amounts of 10 g per pot and 0.5 NPK[1], as well as 20 g of digestate and 1.0 NPK per pot. Similar plant heights were found in the absence of fertilisation (K) and only in the use of digestate (D20). However, over time, the effect of using varied fertilisation became clear. During the harvest, i.e. 1/X, the highest height of sorghum (250 cm) was found after fertilisation with digestate in the amount of 10 g per pot and 0.5 NPK, as well as 20 g digestate and 1.0 NPK per pot. However, the lowest height was found after fertilisation with NPK alone and with digestate only, and the difference with the highest one was 50 cm.

[1] For abbreviation explanations see Table 1.

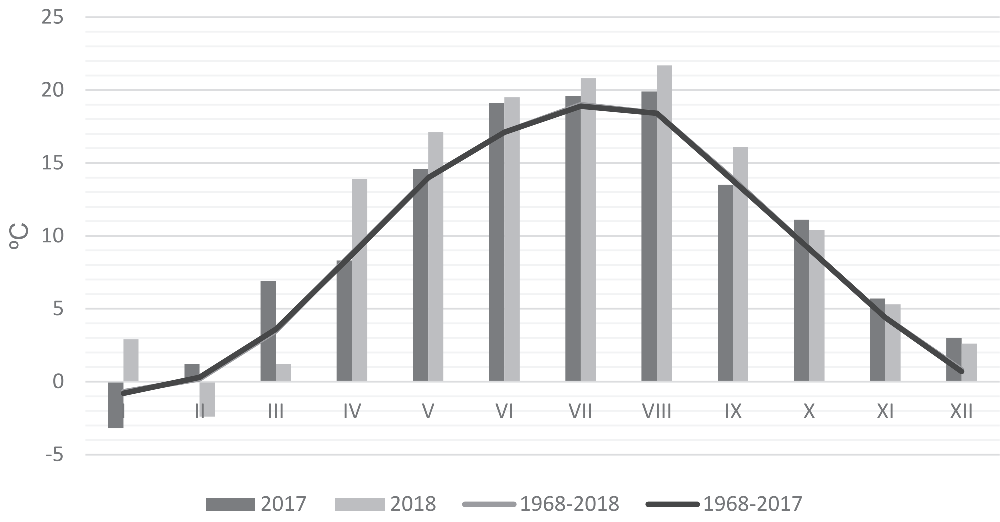

Fig. 1. Thermal conditions.

The chlorophyll content in the tissues (Fig. 3) was clearly different from the content at the beginning of the measurements, i.e. from 2/VI. As the plants developed, these differences clearly increased to reach their maximum between 2/VII and 2/VIII, i.e. during the full vegetation period. At the end of this maize growth period, when the leaves began to wither, the differences were small. Initially, in the case of sites D10-0.5NPK, D20-1NPK and D30-1.5NPK up to 2/VII, the chlorophyll content grew dynamically to the level of 35-37 CCI. However, at the same time, in the remaining variants, the chlorophyll content gradually decreased to 20 CCI. From the 3rd decade of July, the chlorophyll content began to systematically decrease in all tested sites to reach a value of 5-10 CCI at harvest. The highest chlorophyll content was found in plants from sites fertilised with digestate in the amount of 30 g / 1.5 NPK per pot, and the lowest content was found in plants fertilised with NPK alone.

The fourth table summarises the weight results of the fresh and dry mass of sorghum plants. The obtained data indicated a large and significant difference between the two discussed values. The lowest yields of fresh mass from the pot were obtained after applying digestate alone (D20) and in the absence of fertilisation (K). The addition of 0.5 of NPK resulted in a slight, statistically insignificant increase in yield. Only increasing the dose of digestate to 20 g per pot and NPK to 1 g resulted

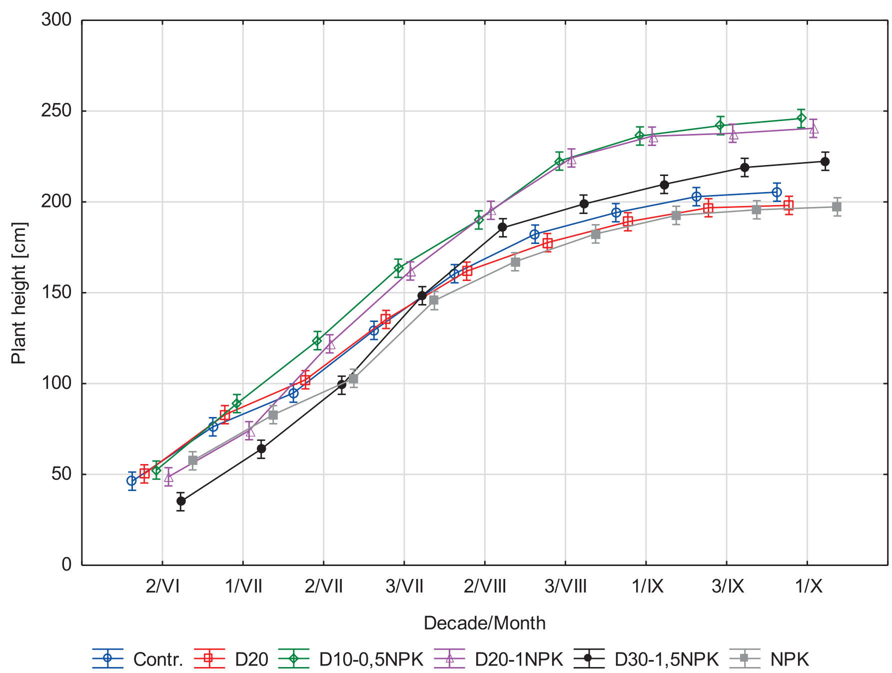

Fig. 2. Sorghum height during vegetation depending on fertilizer type; bar is standard error n = 5; For abbreviation explanations see Table 1.

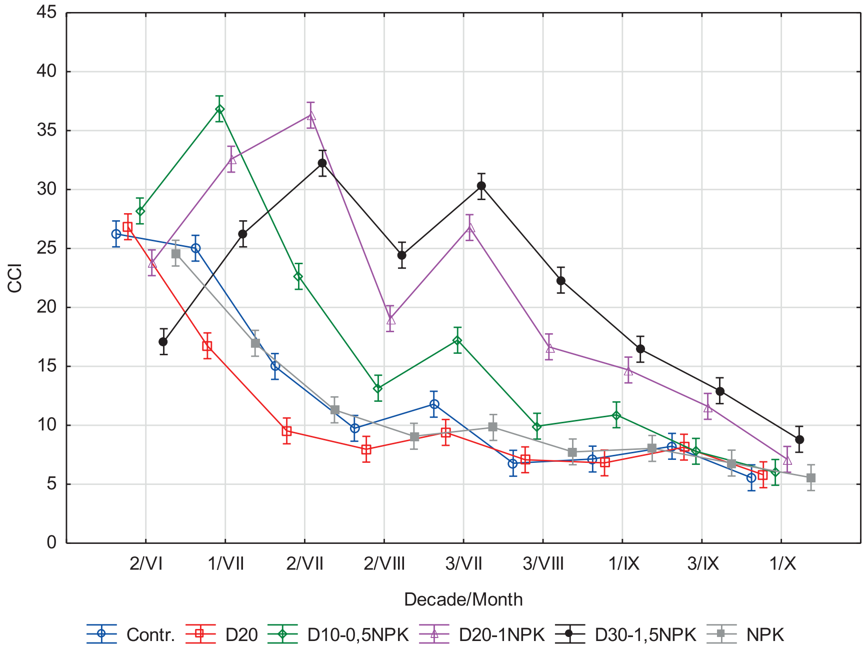

Fig. 3. Chlorophyll content in sorghum during vegetation depending on fertilizer type; bar is standard error n = 5; For abbreviation explanations see Table 1.

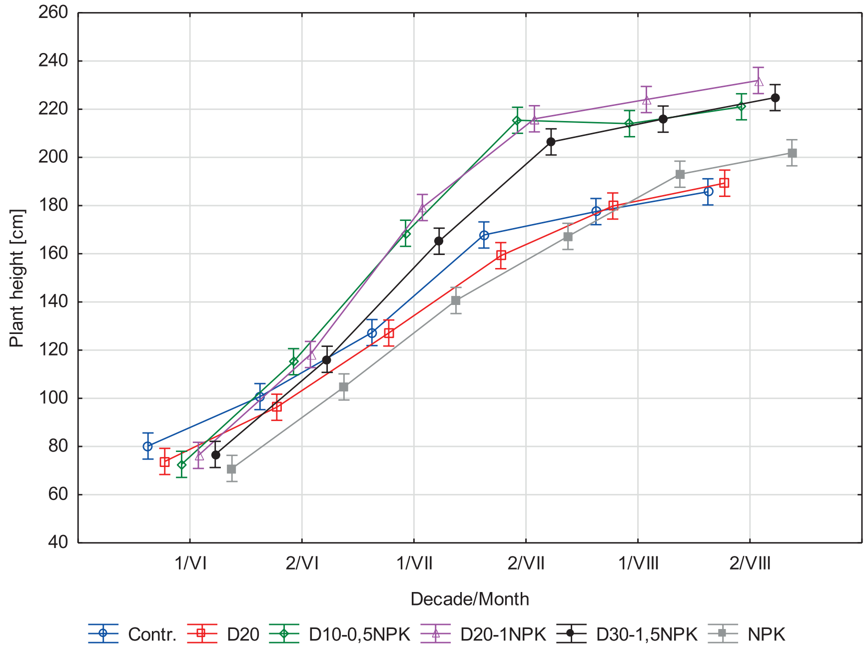

Fig. 4. Maize height during vegetation depending on fertilizer type; bar is standard error n = 5; For abbreviation explanations see Table 1.

in a significant, more than twofold, increase in both the fresh and dry mass. Further increasing the dose of digestate and NPK resulted in a further increase in yield. The highest yield of fresh mass was found in the case of the maximum dose of digestate and NPK, and it was more than two times higher than in the sites with the lowest yield. Similar but not identical dependencies occurred in the case of dry mass. In this case, the highest dry mass yield was obtained after fertilisation with digestate in the amounts of 20 g and 1.0 NPK and 30 g and 1.5 NPK, and the lowest, as in the case of fresh biomass, in the absence of fertilisation and after adding only 20 g of digestate. As for the yields of leaves and stems, the ratios between individual sites were similar.

The height of maize plants clearly depended on the applied level of fertilisation (Fig. 4). The highest height of maize plants during the harvest period was recorded after the use of digestate in the amount of 20 g per pot

Table 4. Fresh and dry mass weight of sorghum aerial parts [g].

Fertilizer type and dose	Fresh plant mass	Fresh leaf mass	Fresh stem mass	Dry plant mass
Contr.	213	73	141	65
D20	204	70	135	59
D10-0,5NPK	380	101	289	123
D20-1NPK	493	124	360	150
D30-1,5NPK	503	144	359	144
NPK	220	73	148	68
$LSD_{0,05}$	120	10	30	20

For abbreviation explanations see Table 1.

and 1.5 NPK and slightly lower 20 g of digestate and 1.0 NPK, as well as on site D30-1.5NPK, where 30 g of digestate and 1.5 NPK was applied. However, in the case of no fertilisation (K) or the use of digestate alone (D20), the lowest plant height was found to be significantly lower – about 40 cm lower from the highest. The growth dynamics at all examined sites were initially very similar. However, in the final phase, there was increasing differentiation in favour of site D10-0.5NPK.

The effect of fertilisation on the chlorophyll content in maize cells clearly varied, especially in the middle stage of maize development, i.e. from the second decade of June to the second decade of July (Fig. 5). At the end of vegetation, the differences decreased significantly, except for those fertilised with the maximum doses of digestate and NPK. In full vegetation, the leaves of plants fertilised with the maximum dose and 20 g of digestate with 1.0 NPK contained significantly more chlorophyll. At the end of the maize vegetation period, most of the differences were no longer significant, with the highest chlorophyll content in plants fertilised with digestate in the amount of 30 g / pot of 1.5 NPK, and the lowest content of plants fertilised with NPK alone.

The results of the fresh and dry mass of maize plants are summarised in Table 5. The presented data indicate a large and significant difference, both in the fresh and dry mass of plants. Its lowest yield of 209 g per pot was obtained in the absence of fertilisation, and after the use of digestate only, the addition of 0.5 of NPK resulted in a significant increase in yield. A further increase of the digestate dose to 20 per pot and NPK to 1 g resulted in a clear, twofold increase in the yield of both the fresh and dry mass of the crop. The highest yields of fresh mass

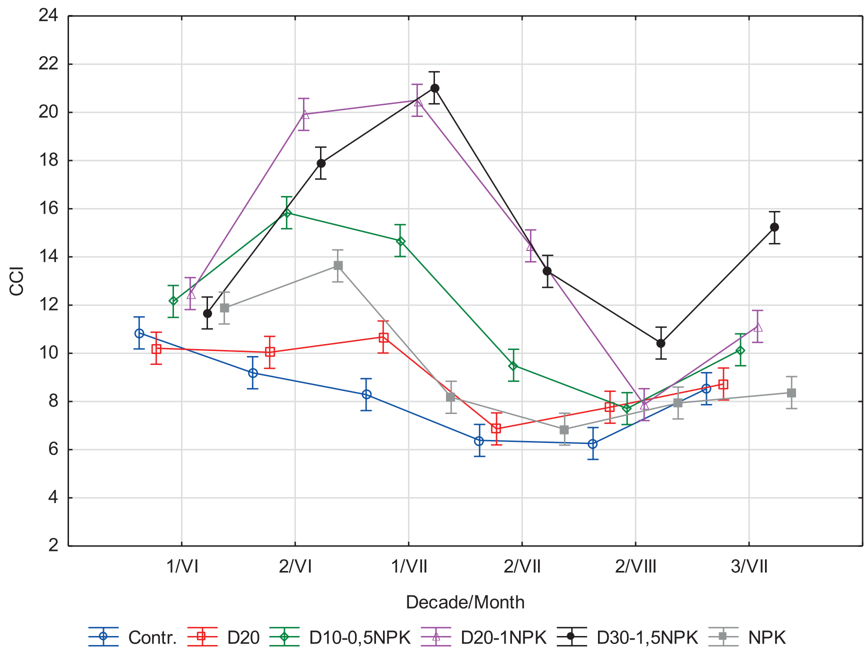

Fig. 5. Chlorophyll content in sorghum during vegetation depending on fertilizer type; bar is standard error n = 5; For abbreviation explanations see Table 1.

Table 5. Fresh and dry mass of the above-ground parts of maize [g] and the number of cobs [pcs.].

Fertilizer type and dose	Fresh cob mass	Fresh stem mass	Fresh leaf mass	Fresh plant mass	Dry plant mass	No. of cobs
Contr.	43	119	50	209	71	1
D20	40	123	49	209	64	0.9
D10-0,5NPK	91	198	71	357	109	1.1
D20-1NPK	142	231	80	446	142	1.2
D30-1,5NPK	172	253	92	512	164	1.9
NPK	58	158	60	273	79	1
$LSD_{0,05}$	10	20	6	31	10	0.36

For abbreviation explanations see Table 1.

were recorded after the application of the maximum dose of digestate and NPK (D30-1.5NPK). The obtained result was almost 2.5 times higher than the one obtained in the variants without fertilisation or after adding 20 g of digestate alone. In the case of dry mass, there were similar dependencies but on a smaller scale. Namely, the highest dry mass yield was obtained after fertilisation with digestate in the amounts of 30 g and 1.5 NPK, and the lowest, similarly to fresh mass (sites K, D20 and NPK). In the case of the yields of leaves, stems and cobs, the ratios between individual objects were similar.

The effect of different fertilisations on soil respiration is clear, both in the case of sorghum and maize (Table 6). In the case of sorghum, the level of respiration increased along with an increase in fertilisation with digestate and NPK, while in the case of maize, a reverse trend was found. Fertilisation with digestate only in the case of sorghum resulted in a very small and insignificant increase in respiration compared to the site without fertilisation. However, an increased level of fertilisation with digestate and NPK (site D10-0.5NPK; D20-1NPK; D30-1.5NPK) resulted in a significant increase in respiration, while the use of NPK alone maintained respiration at the level of sites K and D20. An inverse relation was found in maize. Sites with no fertilisation or with the basic dose of digestate had the highest respiration (0.97 g $CO_2 \cdot m^{-2} \cdot h^{-1}$). Sites with higher doses of digestate and NPK had significantly lower respiration, and sites fertilised with NPK only had the lowest respiration.

Table 6. Soil respiration [g $CO_2 \cdot m^{-2} \cdot h^{-1}$].

Fertilizer type and dose	Plant	
	Sorghum	Maize
Contr.	0.14	0.97
D20	0.17	0.89
D10-0,5NPK	0.23	0.62
D20-1NPK	0.33	0.77
D30-1,5NPK	0.34	0.68
NPK	0.16	0.52
$LSD_{0,05}$	0.06	0.12

For abbreviation explanations see Table 1.

Discussion

The constantly growing demand for energy and the need to reduce greenhouse gas emissions necessitate the search for alternative solutions to obtain fertilisers. In addition, the use of digestate for production is a practical implementation of the idea of a closed circle [21, 22]. The resulting fertiliser is used to fertilise energy crops that will be used for biogas production in the future, and the waste product – digestate – will become a substrate necessary to produce fertiliser.

Many scientific studies confirm the usefulness of digestate as a valuable source of macro- and micronutrients [23-25], but little research has focused on waste processed into an organic mineral fertiliser in granular form. The method of fertiliser incorporation [26] and the nutrient content of the anaerobic digest mainly depend on the type of feedstock and the efficiency of the fermentation process. The granulated fertiliser obtained from digestate is more stable and the chemical composition is predictable; moreover, there is no possibility of N immobilisation [17]. The conducted research demonstrated the usefulness of the mineral fertiliser obtained from digestate in combination with small doses of mineral nitrogen, phosphorus and potassium (enriched digestate). In the case of sorghum, along with the increase in bio-fertiliser doses, the plants responded with an increase in the biomass yield, contained more moisture and were characterised by a higher turgor pressure and chlorophyll content in full vegetation. Sowiński and Liszka-Podkowa [27] and Petersen [28] demonstrated an increase in the sorghum yield by increasing the nitrogen dose, while Buxton et al. [29] did not obtain a significantly lower yield after applying reduced doses of mineral nitrogen. Geng et al. [30] did not obtain a higher sorghum yield after increasing the nitrogen dose above 100 kg · ha^{-1}, whereas Peng et al. [31] showed that reducing the level of nitrogen fertilisation prevents the achievement of the production potential and consequently leads to a reduction in yield. Both Muhammad et al. [18] and Radwan et al. [19] have shown that a combination of mineral and organic nitrogen fertilisation gives better results than applying the whole rate in one form. This is due to improved soil water properties, increased nutrient availability and the immobilisation of some micronutrients.

The usefulness of digestate in increasing the energy efficiency of sorghum has been demonstrated by Głąb et al. [32]. Moreover, Akdeniz et al. [33] obtained the highest yields of dry mass by combining mineral fertilisation with digestate. Mineral nitrogen applications and biosolids-N had a favourable effect on sorghum N uptake.

Verdi's [34] confirmed the possibility of fertilising maize with digestate instead of mineral nitrogen. In the experiment, the highest dry mass yields were obtained by combining digestate with mineral fertilisers. The use of digestate alone or NPK alone led to a significant reduction in growth and yield dynamics. Quakernack [26] and Wolf [35] obtained higher yields with mineral fertilisation but not after digestate was used. Elements of the yield structure, such as the weight of a single cob or the number of cobs per plant, achieved the highest values in variants combining both types of fertilisers. Baryga et al. [7] obtained the highest average cob weight and maize plant height by fertilising with raw digestate derived from sugar beet and not after the application of mineral fertilisation in a dose corresponding to 200 kg·ha^{-1} N.

Conclusions

This research demonstrated that the use of digestate-based fertiliser improves the productivity of both sorghum and maize but only with an additional dose of basic macronutrients. The optimal variant is a fertiliser dose of 20 g enriched with 1.0 NPK. Increasing the dose to 30 g and 1.5 NPK generally did not result in a significant increase in plant height or in fresh and dry weights. The usefulness of the fertiliser from digestate was visible after comparing the results obtained in pots fertilised with NPK only. Plants growing under these conditions were characterised by parameters similar to or slightly better than after using the digestate fertiliser alone or even under control conditions (no additional fertilisation).

Funding

The work was carried out as part of the NCBR PBS/B8/23/2015 project: "Non-waste biogas production from plant substrates based on the transformation of digestate into a valuableorganic-mineral granular fertilizer".

Conflict of Interest

The authors declare no conflict of interest.

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