Sustainable Food Industry 2025, 1(1)

The Efficiency of Using Innovative Soil Liming and Fertilizer Means in Winter Wheat Sowings

Aleksandrs Adamovičs [a1], Liena Poiša [b]

[a] *Latvia University of Life Sciences and Technologies, Lielā str. 2, Jelgava, LV-3001, Latvia*
[b] *Rezekne Academy of Technologies, Atbrivošanas str.115, Rezekne, LV-4601, Latvia*

Abstract

Field trials were conducted at the Study and Research Farm "Peterlauki" of the Latvia University of Life Sciences and Technologies from 2020 to 2023. Soil characteristics: sod - stagnogley soil Luvisols (according to FAO classification); granulometric composition – heavy dusty sand clay. Winter wheat sowings were established using different variants of a fertilizer mix with cattle (from JSC "Ziedi JP") manure digestate (D) and wood ash (P) (from LLC "Gren Jelgava") in different ratios. The norms of the innovative mixed fertilizer for cattle manure digestate and wood ash were 5, 10, and 20 t per ha. Unfertilized winter wheat plots were used as a control. Variants in the two-factor trial were randomized in triplicate. In the experiment, the influence of the researched factors on winter wheat grain yield, the content of protein, starch and gluten in grains, Zeleny index, grain volumetric weight (kg per hL), and the mass of 1000 grains were determined. The aim of the study was to determine the impact of biogas fermentation by-product (digestate) and cogeneration plant and boiler house residues (wood ash) on the yield and quality of winter wheat. Depending on the study variant, the winter wheat yield varied on average three years from 6.29 to 7.39 t per ha. It was established that the average winter wheat grain yield in the control variant was 5.05 t per ha, which is significantly ($p<0.05$) lower than in the variants using fertilizers of digestate and wood ash mixtures. Using digestate and wood ash mixtures, sufficiently high and high-quality winter wheat yields can be obtained without the use of mineral fertilizers. The mixtures of digestate and wood ash are an innovative fertilizer way for improving soil fertility, which is also suitable for winter wheat.

Keywords—digestate, wood ash, mixtures, winter wheat

1. Introduction

Winter wheat (*Tricum* aestivum L.) is considered to be one of the most important grain crops. Due to its high yielding and grain quality they are widely grown and used in food products all over the world. In general winter wheat productivity and yield quality can be affected by a variety of biotic, abiotic and anthropogenic factors, for example meteorological conditions, soil fertility, soil reaction, fertilizer use and various agricultural treatments. The most important measures for improving the productivity and yield quality of winter wheat are soil reaction improvements and plant fertilization. Proper use of various fertilizers not only ensures improvements in yield but also can reduce environmental pollution, thereby improving general quality of life (Hejcman et al., 2011; Jakab et al. 2019). Currently, to produce heat and energy biogas plants and solid fuel boilers are widely used with generating digestate and wood ash as by-products. In normal circumstances, these by-products need to be stored and disposed of which is a complex task that can often pose various environmental pollution risks. Both wood ash and biomass digestate are used as liming and fertilizing agents in agricultural sectors.

Agricultural production must be carried out in accordance with environmental protection requirements. It is important to maintain the safe use of fertilizers, especially nitrogen fertilizers, in the agricultural environment. About 180 million tons of anaerobic digestion digestate is produced in the European Union annually, most of which is used as organic fertilizer (Corden et al., 2019).

[1] Corresponding author

Online ISSN 3044-7224
https://doi.org/10.17770/sfi2025.1.1.8375

Digestate, or fermentation residue, is produced as a by-product under anaerobic conditions in biogas plants and is considered one of the most valuable types of organic fertilizer. It contains valuable macro- and microelements and is a good fertilizer (Dubrovskis et al., 2012; Koszel et al., 2015).

Anaerobic digestion residues are products from various sources of organic raw materials, which include sewage treatment, plant sludge, agri-food industry waste (a part of household solid waste, including fruit and vegetable by-products, canteen waste, kitchen waste), green waste (agricultural and horticultural waste), animal waste (pig, cattle, etc., manure), and food waste (animal fat, used cooking oil, degreasing waste from restaurant tanks) (Bhatt et al., 2020). Digestate is rich in nutrients and can provide a large part of the nutrients needed by plants during the vegetation period, as well as improve soil structure.

The nutrients present in the digestate are in a form that is easily utilized by plants. Approximately 35–81% of the total nitrogen content in digestate is ammonia (NH_4) in a form available to plants. Also, digestate is a plant fertilizer competitive to mineral fertilizers. The organic substances present in digestate have a positive effect on the physical and chemical properties of soil and on the soil fertility in general (Comparetti et al., 2013).

Digestate performs several functions and plays a beneficial role in both improving the soil properties and promoting the plant growth. First of all, digestate contains nutrients necessary for plant growth and serves as a fertilizer that improves plant productivity. Secondly, digestate significantly affects the overall soil fertility and other important soil parameters. Digestate plays an important role in improving soil efficiency by ensuring the cycle of nutrients in the soil, carbon transformation, and maintenance of soil structure (Przygocka-Cyna et al., 2018). Field application of digestate could have less short-term results due to the slow mineralization or microbial activity (Abubaker et al., 2015).

In order to use digestate as an organic fertilizer, it is usually divided into a solid (dry) and a liquid fraction. They differ in dry matter content and chemical composition, which in turn can affect biomass production differently (Hjorth et al., 2010). In agricultural practice, digestate is often used as a fertilizer for crops grown for biomass production, especially for the production of biogas.

As a result of anaerobic fermentation processes, digestate can have higher nitrogen and other nutrient content compared to unfermented manure (Alburquerque et al., 2012; Li et al., 2018), which in turn can affect fertilizer efficiency and yield. Some short-term studies have found lower nitrogen use efficiency for organic fertilizers (slurry, digestate) compared to mineral fertilizers (Schröder, 2005), which is probably related to the risk of nitrogen losses due to leaching and ammonium emissions (Gutser et al., 2005; Sänger et al., 2014). However, long-term studies have observed a positive effect of organic fertilizer on crop yield, which depends not only on the amount of nitrogen applied to plants, but also on other aspects of organic fertilizer use related to changes in soil fertility (Sørensen, 2004; Schröder et al., 2007).The different results of studies on the effect of digestate on wheat yield are explained by the interaction of many factors, including dose and substrate type (Koszel et al., 2016; Abubaker et al., 2017). The effect of digestate on crop yield depends on many factors, such as soil properties, climatic conditions during the growing season, chemical composition of the digestate and application methods (Riva et al., 2016; Panuccio et al., 2018). Studies in England compared the effects of digestate and mineral fertilizers on winter wheat yield: the nitrogen rate for both types of fertilizer were N250 kg ha^{-1}. No significant differences in biomass and grain yield were found between the use variants of digestate (respectively 19.2 t ha^{-1} and 11.3 t ha^{-1}) and mineral fertilizers (respectively 19.6 t ha^{-1} and 11.6 t ha^{-1}). Also, when analyzing the protein content in grains, no significant differences were found between the use variants of digestate and mineral fertilizers (11.52% and 11.06%, respectively) (Udall et al., 2017). In other studies, when digestate fertilizer was used, a higher protein content was found in wheat grains compared to the mineral fertilizer variant, but no significant differences in starch content were found (Różylo et al., 2015). Due to the significant increase in the cost of mineral fertilizers and their more difficult availability, it is necessary to find alternatives to the use of mineral fertilizers and improve soil fertility as soon as possible.

Wood ash, a by-product of biomass combustion, can return important nutrients to the soil and prevent its acidification. Soil pH can be regulated by using various soil liming materials (e.g. dolomite flour, lime) or wood ash. In recent years, due to the increase in the volume of biomass combustion for heat production, the production of wood ash as a by-product has increased significantly. Wood ash consists of inorganic compounds from the obtained biomass, sand residues and a very small part of unburned organic material (Ingerslev et al., 2011). Thus, wood ash contains all inorganic macro- and microelements present in plant biomass, except N (Augusto et al., 2008; Demeyer et al., 2001). During combustion, various oxides are formed, and subsequent aeration leads to the formation of carbonates in the wood ash, which makes the ash highly alkaline, with a pH of 8 to 12 (Augusto et al., 2008). Unlike landfilling ash, recycling ash as a soil amendment returns important nutrients to the soil and prevents acidification (Pitman, 2006).

The aim of the study was to determine the impact of biogas fermentation by-product (digestate) and cogeneration plant and boiler house residues (wood ash) on the yield and quality of winter wheat.

2. Materials and Methods

A field trial was conducted at the "Peterlauki" Study and Research Farm (56°53' N, 23°71' E) of the Latvia University of Life Sciences and Technologies (LBTU) from 2020 to 2023. Soil characteristics: sod calcareous soil Luvisols (according to FAO classification); granulometric composition: heavy dusty sand clay. Soil agrochemical parameters: pH KCL 6.7 (LVS ISO 10390: 2006); organic matter content: 26 g kg^{-1} (by Tyurin method, LV ST ZM 80-91), the phosphorus (P_2O_5) and potassium (K_2O) level – 60 mg kg^{-1} and 144 mg kg^{-1}, respectively (according to Egner-Rhym method, LV ST ZM 82-97).

A two-factor experiment was set up: 1) mixtures of cattle manure digestate (from JSC "Ziedi JP") (D) and wood ash (from LLC "Gren Jelgava") (P) with different component proportions (D+P 1:0; D+P 1:1; D+P 2:1; D+P 3:1; D+P 3:1 + NPK 8-20-30 200 kg ha^{-1}, in autumn; D+P 3:1 + N 64 kg ha^{-1}, in spring; D+P 4:1); 2) different norms of mixtures used for fertilization (5 t ha^{-1}, 10 t ha^{-1}, 20 t ha^{-1}). The nutrient content of the digestate and wood ash mixtures are given in Table 1.

TABLE I. TABLE 1 NUTRIENT CONTENT OF THE DIGESTATE AND WOOD ASH MIXTURES

Nutrients	Content in dry matter, %			
	D+P 1:0	*D+P 1:0*	*D+P 1:0*	*D+P 1:0*
Nitrogen in the natural sample (N)	0.29	0.27	0.30	0.51
Ammonium nitrogen (N/NH_4), g kg^{-1}	1.20	0.43	0.40	0.76
Phosphorus (P),	0.74	0.90	0.89	0.83
Potassium (K),	1.70	2.90	2.92	2.73

D –*cattle manure digestate*; P –*wood ash*

Winter wheat fields fertilized only with digestate were used as control variants. Variants in the experiment were arranged randomly, in three replications. The size of each individual plot in the replications was 30 m^2. Winter wheat pre-crop – fallow. All previously prepared mixtures of cattle digestate and wood ash were spread in the plots prepared before sowing. The mixtures were incorporated into the soil with the combined soil tiller "Farmet Kompaktomat K400", which simultaneously crumbles and levels the soil while applying fertilizer. The winter wheat variety 'Zeppelin' was used for sowing; sowing rate – 500 germinating seeds per m^2. Sowing depth – 3–4 cm; row spacing – 12.5 cm. The experimental plots were sown with a seed-drill "Wintersteiger plotseed H". In the spring, when vegetation was restored, 200 kg ha^{-1} ammonium nitrate (N 34.4%) was incorporated into the plots of the trial variant D+P 3:1+N.

Fig 1. Winter wheat sowings in field trials

Harvesting was carried out with a small-sized combine harvester "Sampo". After threshing of the experimental plots, the yield of each plot was weighed and cleaned using the "PFEUFFER SLN3" sample cleaning device. Qualitative indicators were determined at the Biotechnology Scientific Laboratory (BSL) of the Latvia University of Life Sciences and Technologies (LBTU). Using the express analyser "Infratec NOVA Foss", the moisture content of the samples, the total nitrogen and starch content in the grains (%), and the bulk density (kg hL^{-1}) were determined. Using the obtained result, the obtained yield (t ha^{-1}) was calculated at 14% standard moisture and complete (100%) sample purity. For the samples, the weight of 1000 seeds, in grams, was also determined using the standard method (LVS EN ISO 520).

The meteorological conditions in all three trial years differed from the long-term average. Autumn 2020 was long and cool, 2021 was relatively warm and dry, and 2022 was similarly warm and dry. All winters during the trial period were mild and favourable for winter wheat. Vegetation re-emerged in all years in early April.

Spring 2021 was warm with sufficient moisture; summer was rainy, especially with high precipitation in July, but precipitation decreased in August.

Spring 2022 was moderately warm and humid; however, summer in June and August was dry, with high precipitation in July.

Spring 2023 was warm with low precipitation, but summer in June and August was dry.

The data were statistically analysed using a two-way analysis of variance (ANOVA) with different norms of mixtures and different component proportions in mixtures as factors, and the difference among means was detected by LSD at the $p < 0.05$ probability level (Excel for Windows, 2003).

3. Results and discussion

Winter wheat grain yield. All studied factors showed a significant effect on grain yield. All used digestate and wood ash rates, starting from the lowest (5 t ha^{-1}) to the highest (20 t ha^{-1}), significantly affected the increase in grain yield compared to the control. On average, the winter wheat yield in the study variants over the three years was 6.29-7.39 t ha^{-1}. This was 1.24 -2.34 t ha^{-1} or 24.6-46.3% more than in the control variant (without fertilizer). During the research years, winter wheat yield, depending on the research variants, varied from 4.26 to 9.40 t ha^{-1} (Table 2).

TABLE 2 THE EFFECT OF DIGESTATE AND WOOD ASH MIXTURES ON WINTER WHEAT GRAIN YIELD, T HA^{-1}

Fertilizer rate, t ha^{-1} (FA)	Digestate and wood ash ratio in the mixture, D+P (FB)	Years of field trials			On average in three trial years
		2021	*2022*	*2023*	
5	1: 0	7.40	4.83	4.26	5.85

Fertilizer rate, t ha^{-1} (FA)	**Digestate and wood ash ratio in the mixture, D+P (FB)**	**Years of field trials**			**On average in three trial years**
		2021	***2022***	***2023***	
	1: 1	7.30	5.33	4.28	5.86
	2: 1	7.40	5.92	4.69	6.11
	3: 1	7.20	5.05	4.55	6.14
	3: 1+NPK	7.40	6.10	4.69	6.32
	3: 1+N	8.50	7.88	7.39	7.96
	4:1	7.40	5.36	4.31	5.79
	On average	**7.51**	**5.78**	4.88	**6.29**
10	1: 0	8.50	4.78	5.06	5.76
	1: 1	8.30	5.00	5.69	6.11
	2: 1	8.50	5.15	5.59	6.30
	3: 1	8.60	5.28	5.38	5.88
	3: 1+NPK	8.60	5.67	5.41	6.30
	3: 1+N	9.20	7.29	7.79	8.06
	4:1	7.90	5.16	5.31	6.02
	On average	**8.51**	**5.48**	**5.75**	**6.35**
20	1: 0	7.90	5.02	6.53	6.48
	1: 1	8.00	5.76	6.58	6.78
	2: 1	7.90	6.63	6.60	7.04
	3: 1	7.90	6.89	7.12	7.30
	3: 1+NPK	8.10	7.02	7.38	7.50
	3: 1+N	9.40	8.31	9.03	8.91
	4:1	7.80	8.33	7.10	7.74
	On average	**8.14**	**6.85**	**7.19**	**7.39**
Control	0 :0	**6.80**	**4.31**	**4.03**	**5.05**
$LSD_{0.05}$ A		0.24	0.53	**0.39**	**0.39**
$LSD_{0.05}$ B		0.39	0.86	**0.59**	0.61
$LSD_{0.05}$ AB		0.68	1.49	1.02	1.06

D- cattle manure digestate, P- wood ash

The results showed that the average yield of wheat grain in all three years of the study was very high at all studied fertilizer rates, when mineral nitrogen was added to the digestate and wood mixture, variant 3:1+N., The grain yield in this variant was on average 7.96-8.91 t ha^{-1} but the lowest yields were obtained in the variant with a digestate-ash ratio of 1:0, in which ash was not used (Table 2). This can be explained by the fact that digestate and wood ash mixtures, as fertilizer, provide plants mainly with phosphorus and potassium and a nitrogen deficiency is observed. The trends in the influence of the ratio of digestate and wood ash in the mixtures on wheat grain yield were the same in all years of the study. Better results were obtained when this ratio was 3:1.

Grain yield depended on the amount of fertilizer used, as well as the digestate and wood ratio in the mixture (Table 2). The fertilizer rate significantly ($p<0.05$) increased the winter wheat yield in 2021 – on average by 0.71-1.34 t ha^{-1} or 5,20-19,70 %, compared to the unfertilized control variant. In this year, significant grain yields were obtained in all studied variants compared to 2022 and 2023. The lower grain yield in these years is explained by unfavorable meteorological conditions, when a very severe drought was observed precisely during the grain formation period. Using wood ash and digestate mixtures, it is possible to significantly ($p<0.05$) increase the grain yield of winter wheat.

Wheat grain's chemical composition makes it a staple crop with versatile uses in various food products worldwide. Wheat grain consists primarily of carbohydrates (70–75%), mainly in the form of starch, followed by protein (10–15%), fats (1–2%), vitamins (such as B-vitamins), minerals (like iron and magnesium), fiber (2–3%), and water (10–15%) (Simon et.al.,2020; Khalid et. al.2023).

The applied fertilizer rate had a significant ($p<0.05$) effect on the following wheat quality indicators: protein content, gluten content, starch content in dry matter, Zeleny index, volume weight and 1000-grain weight.

Protein (CP) content of winter wheat grain. Protein content in grain is the most important indicator of wheat grain quality. Wheat proteins, particularly gluten, play a significant role in determining the dough's strength, elasticity, and extensibility, which ultimately determine the quality of baked products (Ooms et al., 2019). The gluten proteins contribute to the structure of bread by forming a strong and elastic network that traps gases produced by yeast during fermentation, leading to a well-risen and airy bread.

The control variant had an average protein content of 9.52% versus the average protein content of wheat grain was significantly higher ($p<0.05$) with any fertilizer variant, ranging from 10.02% to 11.94%. The highest protein content – was obtained from plots fertilized with D+P 3:1 + N 64 kg ha^{-1}. Among fertilized rates significantly higher average protein content of 12.4% was obtained from plots fertilized with variant of 10 t ha^{-1}.

Significantly higher protein content in dry matter was found when using lower (5 and 10 t ha^{-1}) fertilizer rates, while the lowest indicators were found when using a 20 t ha^{-1} fertilizer rate (Table 3).

TABULA 3 EFFECT OF DIGESTATE AND WOOD ASH MIXTURE ON PROTEIN CONTENT IN WINTER WHEAT GRAINS, %

Fertilizer rate, t ha^{-1} (FA)	Digestate and wood ash ratio in the mixture, D+P(FB)	Years of field trials			On average in three trial years
		2021	*2022*	*2023*	
5	1: 0	11.00	11.07	9.40	10,49
	1: 1	11.40	10.23	9.50	10,38
	2: 1	10.70	10.83	9.40	10,31
	3: 1	11.00	10.90	9.27	10,39
	3: 1+NPK	10.70	10.67	9.13	10,17
	3: 1+N	14.60	10.57	10.53	11,90
	4:1	10.80	10.83	9.40	10,34
	On average	**11.46**	**10.73**	**9.52**	**10,57**
10	1: 0	12.10	10.17	8.50	10,26
	1: 1	12.00	9.90	9.07	10,32
	2: 1	12.20	10.90	8.40	10,50
	3: 1	12.10	9.93	9.17	10,40

Fertilizer rate, t ha^{-1} (FA)	Digestate and wood ash ratio in the mixture, D+P(FB)	Years of field trials			On average in three trial years
		2021	*2022*	*2023*	
	3: 1+NPK	12.80	9.97	8.53	10,43
	3: 1+N	14.30	10.37	10.77	11,81
	4:1	11.60	10.63	8.17	10,13
	On average	**12.44**	**10.27**	**8.94**	**10,55**
20	1: 0	10.50	10.67	9.63	10,27
	1: 1	10.50	9.80	10.00	10,10
	2: 1	10.30	9.97	9.80	10,02
	3: 1	10.70	10.50	10.33	10,51
	3: 1+NPK	11.10	10.17	9.87	10,38
	3: 1+N	13.80	10.80	11.23	11,94
	4:1	10.90	10.13	10.07	10,37
	On average	**11.11**	**10.29**	**10.13**	**10,51**
Control	0 :0	**10.4**	**10.13**	**8.02**	**9.52**
LSD $_{0.05}$ A		0.31	0.24	0.21	**0.24**
LSD$_{0.05}$ B		0.50	0.31	0.29	0..32
LSD $_{0\text{-}05}$ AB		0.68	0.42.	0.38	0.44

D- cattle manure digestate, P- wood ash

The standards for food quality wheat grain CP content are from 12% (https://dzirnavnieks.lv/lv/graudu-piegadatajiem). To achieve higher protein more nitrogen is required to fulfil the higher demand. Grain protein with optimum N for yield in feed wheat is consistently around 11% (equivalent to 1.9% N). However, bread making wheat optimizes for yield at around 12% protein and will often need extra nitrogen to achieve a market specification of over 13%. Low grain protein i.e. less than 10% for feed varieties, indicates sub-optimal nitrogen use.

Conditions of growing season affected significantly the grain protein content. In all studied variants, on average, the highest protein content was observed in growing season 2020/2021 (11.11- 11.46 %). In this year, the plants were better secured with moisture and contributed to better use of the nutrients from the soil. Lower protein content in the grains was observed during the growing season 2021/2022 (10.27- 107.3%) and 2022/2023 (8.94 - 10.13%).

Gluten content of winter wheat grain. An important indicator of the baking properties of bread is the gluten content in wheat grains. Wheat grains with a gluten content higher than 23% are suitable for baking bread. The gluten and its resulting functions are essential to determining the dough quality of bread and other baked products such as pasta, cakes, pastries, and biscuits. Gluten is heat stable and has the capacity to act as a binding and extending agent and is commonly used as an additive in processed foods for improved texture, flavor, and moisture retention (Biesiekierski, 2017).

The amount and quality of gluten are one of the physical indicators of the quality requirements of cereals, for example, for good white bread, wheat flour with at least 23% gluten is required. The quality of wheat gluten is determined by the ratio of the amino acid groups gliadin and glutenin, which should be optimally 1:1.2. Of these, gliadin provides the dough with stretchability, and glutenin — elasticity and firmness (Zarins et al., 2015).

Gluten content (%) in grains significantly ($p<0.05$) differed depending on the year of the study, and a trend for differences depending on the fertilizer rates and mixture composition was observed. Gluten content had a significant close relationship with protein content. Significant differences in gluten content existed between all study years, the highest gluten content was in 2021 – 24.01-27.19%, followed by 2022 – 18.14-19.58%, and 2023 – 15.53 -17.77 percent. The highest gluten content was in variant 3: 1+N at all fertilizer rates. The average for the three years was 23.46 percent (Table 4).

TABLE 4 EFFECT OF DIGESTATE AND WOOD ASH MIXTURE ON GLUTEN CONTENT IN WINTER WHEAT GRAINS, %.

Fertilizer rate, t ha^{-1} (FA)	**Digestate and wood ash ratio in the mixture, D+P (FB)**	**Years of field trials**			**On average in three trial years**
		2021	***2022***	***2023***	
5	1: 0	22.90	20.67	16.10	19.89
	1: 1	24.10	18.13	16.27	19.50
	2: 1	22.10	20.17	16.07	19.45
	3: 1	22.90	20.00	15.63	19.51
	3: 1+NPK	21.80	19.43	15.73	18.99
	3: 1+N	32.20	19.03	18.80	23.34
	4:1	22.10	19.60	15.93	19.21
	On average	**24.01**	**19.58**	**16.36**	19.98
10	1: 0	26.80	17.93	14.67	19.80
	1: 1	25.60	17.13	15.77	19.50
	2: 1	27.00	20.00	14.53	20.51
	3: 1	25.60	17.00	15.47	19.36
	3: 1+NPK	28.80	17.27	14.53	20.20
	3: 1+N	32.00	18.47	19.53	23.33
	4:1	24.50	19.20	14.23	19.31
	On average	**27.19**	**18.14**	**15.53**	20.29
20	1: 0	21.30	19.23	16.73	19.09
	1: 1	21.20	16.80	17.40	18.47
	2: 1	20.40	17.33	16.97	18.23
	3: 1	21.60	18.70	18.10	19.47
	3: 1+NPK	23.30	18.10	16.97	19.46
	3: 1+N	30.50	19.93	20.70	23.71
	4:1	22.50	17.83	17.50	19.28
	On average	**22.97**	**18.27**	**17.77**	19.67
Control	0 :0	**21.3**	**17.04**	14.01	**17.45**
LSD $_{0.05}$ A		0.94	0.81	**0.74**	**0.86**

Fertilizer rate, t ha^{-1} (FA)	Digestate and wood ash ratio in the mixture, D+P (FB)	Years of field trials			On average in three trial years
		2021	*2022*	*2023*	
LSD$_{0.05}$ B		1.15	1.02	**1.13**	1.18
LSD $_{0\text{-}05}$ AB		1.85	1.54	1.97	1.74

D- cattle manure digestate, P- wood ash

The required amount of gluten and/or the optimal ratio of gliadin to glutenin in grains may not be formed due to adverse weather conditions, lack of nutrients, plant diseases, premature grain harvesting, and other reasons (Kunkulberga et al., 2010).

The results of our trial show that the control variant had a gluten content of 17.45%, while the different fertilizer treatments had significantly ($p<0.05$) higher average gluten content of winter wheat grain, ranging from 19.67 to 20.29% depending on fertilizer rate and mixture composition ($p<0.05$). Similarly to protein content, also gluten content in grain increased significantly fertilizer rate 5 t ha^{-1} and the next significant increase was secured by10 t ha^{-1}. The lowest border of food demand of gluten content was obtained when fertilizer rate 20 t ha^{-1} was used. The highest gluten content was obtained for the variants fertilized with fertilizer mixtures D+P 3:1 + N 64 kg ha^{-1}.

These results are in agreement with other studies that determined nitrogen fertilization has a positive impact on gluten content of grain and the content of nitrogen substances is closely related to the gluten content in grain (Kozlovsky et al., 2009).

Results show that the growing season also had a significant impact on gluten content, and explanation can be the same as for protein content.

Zeleny index. Zeleny index or sedimentation value, determines quantity and quality of gluten proteins (Kozlovsky et al., 2009). Evaluation of the data regarding Zeleny index showed that in the control variant the Zeleny index was 24.32 mL and with the addition of any fertilizer variants the Zeleny index increased significantly ($p<0.05$) from 20.58 to 41.60.1 mL (Table 5). In all the study years, the highest Zeleny index, on average 37.06 mL, was obtained from the D+P 3:1 + N 64 kg ha^{-1} fertilizer variants. Among the fertilizer norms of 5, 10 un 20 t ha^{-1} a significantly higher ($p<0.05$) mean Zeleny index compared to control plots was obtained, while the highest mean Zeleny index value 37.66 mL was obtained from fields where 10 t ha^{-1} fertilizer norms were used.

The growing season affected the Zeleny index significantly. More favorable conditions for higher Zeleny index formation were in 2020/2021 when also the highest average protein content in grain accumulated.

TABULA 5 EFFECT OF DIGESTATE AND WOOD ASH MIXTURE ON ZELENY INDEX IN WINTER WHEAT GRAINS, ML

Fertilizer rate, t ha^{-1} (FA)	Digestate and wood ash ratio in the mixture, D+P (FB)	Years of field trials			On average in three trial years
		2021	*2022*	*2023*	
5	1: 0	33.3	26.15	26.00	28.48
	1: 1	34.6	20.6	26.15	27.12
	2: 1	31.3	24.09	26.08	27.16
	3: 1	31.9	24.06	25.94	27.30
	3: 1+NPK	31.4	23.36	25.74	26.83
	3: 1+N	55.5	21.68	32.80	36.66
	4:1	31.5	23.57	26.39	27.15
	On average	**35.64**	**23.36**	**27.01**	28.67

Fertilizer rate, t ha^{-1} (FA)	Digestate and wood ash ratio in the mixture, D+P (FB)	Years of field trials			On average in three trial years
		2021	*2022*	*2023*	
10	1: 0	39.3	19.88	22.99	27.39
	1: 1	37.9	18.85	25.04	27.26
	2: 1	40.2	23.86	24.08	29.38
	3: 1	38.9	18.68	24.41	27.33
	3: 1+NPK	43.7	19.38	23.99	29.02
	3: 1+N	55.1	22.58	35.29	37.66
	4:1	36.1	22.66	21.85	26.87
	On average	**41.60**	**20.84**	**25.38**	29.27
20	1: 0	31.1	22.15	28.75	27.33
	1: 1	30.0	17.9	29 .50	23.95
	2: 1	29.3	19.41	28.04	25.58
	3: 1	31.0	21.55	31.16	27.90
	3: 1+NPK	32.6	19.91	28.06	26.86
	3: 1+N	49.8	23.42	37.35	36.86
	4:1	32.8	19.69	29.94	27.48
	On average	**33.80**	**20.58**	**30.55**	28.31
Control	0 :0	**29.60**	**19.04**	**21.14**	24.32
$LSD_{0.05}$ A		1.62	1.34	1.69	1.52
$LSD_{0.05}$ B		2.64	2.07	2.58	2.34
$LSD_{0\text{-}05}$ AB		4.57	3.89	4.47	4.15

D- cattle manure digestate, P- wood ash

Starch content. Starch constitutes the major carbohydrate in the endosperm of wheat grains and serves as a multifunctional ingredient for the food or nonfood industries. Starch plays a significant role in the texture, stability, appearance, and nutritional value of food products. (Ai et al., 2018; Shevkani et al., 2017). Starch, as the main component of wheat comprising about 60–75 % of grain and 70–80 % of flour, has a number of food and industrial applications (Shevkani et al., 2017). Starch comprises the main source of calories in bread and other wheat-based food products.

In all the years of the study, the effect of the composition of the digestate and wood ash mixtures and the fertilizer rates did not differ significantly between the studied variants. The total starch content in analysed wheat fertilizer variants ranged from 66.35 to 70.80%, with an average 69.70 percent (Table 6).

Analysis of the results of winter wheat grains showed that the starch content in the control variant was 70.32%, while the use of any fertilizer variant minimally changed the starch content in the range from 61.68 to 71.60 percent.

TABULA 6. EFFECT OF DIGESTATE AND WOOD ASH MIXTURE ON STARCH CONTENT IN WINTER WHEAT GRAINS, %

Fertilizer rate, t ha^{-1} (FA)	Digestate and wood ash ratio in the mixture, D+P (FB)	Years of field trials			On average in three trial years
		2021	*2022*	*2023*	
5	1: 0	70.97	67.53	71.40	69.97
	1: 1	70.63	68.57	71.37	70.19
	2: 1	71.27	67.53	71.47	70.09
	3: 1	71.10	67.67	71.43	70.07
	3: 1+NPK	71.07	68.20	71.50	70.26
	3: 1+N	66.33	61.68	71.03	66.35
	4:1	71.20	69.57	71.63	70.80
	On average	**70.37**	**67.25**	**71.40**	**69.67**
10	1: 0	70.33	68.47	71.60	70.13
	1: 1	69.93	68.93	71.23	70.03
	2: 1	69.77	67.43	71.93	69.71
	3: 1	69.77	68.90	71.30	69.99
	3: 1+NPK	69.10	68.73	71.50	69.78
	3: 1+N	66.60	62.54	70.87	66.67
	4:1	70.67	68.96	70.83	70.15
	On average	**69.45**	**67.71**	**71.32**	**69.49**
20	1: 0	71.53	67.90	71.07	70.17
	1: 1	71.40	68.70	71.10	70.40
	2: 1	71.70	68.90	71.20	70.60
	3: 1	71.40	68.03	70.80	70.08
	3: 1+NPK	71.10	68.10	70.87	70.02
	3: 1+N	67.53	67.60	70.07	68.40
	4:1	71.27	68.03	70.70	70.00
	On average	**70.85**	**68.18**	**70.83**	**69.95**
Control	0 :0	**71.60**	**68.10**	**71.25**	**70.32**
$LSD_{0.05}$ A		0.29	0,18	0.25	0.22
$LSD_{0.05}$ B		0.48	0.31	0.39	0.37
$LSD_{0\cdot05}$ AB		0.83	0.48	0.67	0.59

D- cattle manure digestate, P- wood ash

The lowest average starch content of 66.8% was obtained from fertilizer variant D+P 3:1 + N 64 kg ha^{-1}. Addition of mineral nitrogen to the digestate and wood mixture fertilizer in all years of the trial reduced the starch content in wheat grains. Our study confirmed the negative relationship between protein and starch content in grain once more: protein content decreased if starch content increased. All obtained starch results depending on mentioned factors were opposite to protein content.

Among the fertilizer rates applied, lower starch content was in the trial fields where norm of 10 t ha^{-1} was used. Starch constitutes the major carbohydrate in the endosperm of wheat grains and serves as a multifunctional ingredient for the food or nonfood industries. Starch plays a significant role in the texture, stability, appearance, and nutritional value of food products. (Ai, Jane, 2018; Shevkani et al., 2017). Starch, as the main component of wheat comprising about 60–75 % of grain and 70–80 % of flour, has a number of food and industrial applications (Shevkani et al., 2017). Starch comprises the main source of calories in bread and other wheat-based food products.

Volume mass. It is an indicator of flour outcome at milling enterprise (Kozlovsky at al., 2009). Grain volume indicates grain density. This is mainly determined by the genetic characteristics of the varieties, but improper fertilization of the plants can reduce it. Higher volume weight indicates better grain maturation and richness with nutrients.

Our experiments have shown that using digestate and wood ash mixtures for fertilizing wheat crops can produce high-quality grains with a bulk density of 73-75 kg hL^{-1}, which is comparable to the bulk density of wheat.

Weight of 1000 grains. In the control variant, the weight per 1000 seeds was 39,9g and using different type of fertilizers it is possible to increase 1000 seed weight. Fertilized fields had 1000 seed weight of 40.8 till 43.5g. Significantly ($p<0.05$) higher 1000 seed weights were obtained with 10 or20 t ha^{-1} fertilizer norms.

4. Conclusions

Mixtures of digestate and ash can be used to produce high quality fertilizers, which can increase the productivity of various crops, including winter wheat.

The mixtures of digestate and wood ash are an innovative way for improving the soil fertility.

The results of the study showed that using digestate and wood ash mixtures, sufficiently high and high-quality winter wheat yields can be obtained without the use of mineral fertilizers. Significantly higher ($p<0.05$) winter wheat grain yield was obtained in the variant D+P 3:1 + N and D + P 3:1 + NPK.

It has been observed that to improve the quality of the winter wheat harvest, in addition to this fertilizer, it is recommended to use nitrogen mineral fertilizers.

It has been found that among the studied variants, significantly higher protein and gluten content, as well as Zeleny index, was provided by the fertilizer mixture D + P 3:1 + N, regardless of the fertilizer rate.

References

Abubaker J., Elnesairy N., Ahmad S. (2017). Effects of non-digested and anaerobically digested farmyard manures on wheat crop cultivated in desert soil. *Journal of Arid Land*, 3, p. 1–10.

Abubaker J., Risberg K., Jönsson E., Dahlin A.S., Cederlund H., Pell M. (2015). Short-term effects of biogas digestates and pig slurry application on soil microbial activity. *Applied and Environmental Soil Science*. Available: https://www.hindawi.com/journals/aess/2015/658542/ (viewed 18.02.2024).

Ai Y., Jane, J. (2018). Understanding starch structure and functionality. In Starch in Food, p. 151-178. Woodhead Publishing. https://dx.doi.org/10.1016/B978-0-08-100868-3.00003-2

Alburquerque J. A., Fuente C., Ferrer-Costak A., Carrasco L., Cegarra J., Abad M. (2012). Assessment of the fertiliser potential of digestates from farm and agroindustrial residues. *Biomass Bioenergy*, 40, p. 181–189.

Augusto, L., Bakker M. R., Meredieu C. (2008). Wood ash applications to temperate forest ecosystems—potential benefits and drawbacks. *Plant and Soil*. Vol. 306, No. 1/2, Part I: Special Issue, p. 181-198.

Biesiekierski J. R. (2017). What Is Gluten? J. Gastroenterol. Hepatol. 32 (Suppl. S1), p. 78–81. doi: 10.1111/jgh.13703.

Bhatt A.H., Tao L. (2020). Economic perspectives of biogas production via anaerobic digestion.

Demeyer A., Nkana J.C.V, Verloo M.G. (2001). Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview. *Bioresour Technol*, Vol.77, p. 287–295

Comparetti A., Febo P., Greco C., Orlando S. (2013). Current state and future of biogas and digestate production. *Bulgarian Journal of Agricultural Science*, 19, p. 1–14.

Corden C., Bougas K., Cunningham E., Tyrer D., Kreißig J., Crookes M. (2019). Digestate and Compost as Fertilisers: Risk Assessment and Risk Management Options. Wood Environment & Infrastructure Solutions UK Limited; Aberdeen, UK. Available: https://ec.europa.eu/environment/chemicals/reach/pdf/40039 Digestate and Compost RMOA—Final report i2_20190208.pdf. (viewed 20.02.2024).

Dubrovskis V., Adamovics A. (2012). Bioenerģijas horizonti. Jelgava. p. 352.

Gutser R., Ebertseder T., Weber A., Schraml M., Schmidhalter U. (2005). Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land. *Journal of Plant Nutrition and Soil Science*, 168, p. 439–446.

Ingerslev M., Skov S. Sevel L and. Pedersen L. B. (2011). Element budgets of forest biomass combustion and ash fertilization – A Danish case-study. *Biomass and Bioenergy*. Vol. 35(7), p. 2697-2704.

Hjorth M., Christensen K. V., Christensen M. L., Sommer S. G. (2010). Solid-liquid separation of animal slurry in theory and practice. *Agronomy for Sustainable Development*, 30, p.153–180.

Hejcman M., Ondracek J., Smrz Z. (2011). Ancient waste pits with wood ash irreversibly increase crop production in Central Europe. *Plant and Soil*. Vol. 339 (1), p. 341 – 350.

Jakab P., Festo D., Zoltan G., Komarek L. (2019). The effect of different fertilizer tratments on the yield and quality of winter wheat. *Review on Agriculture and Rural Development*. Vol. 6 (1 – 2), p. 182 – 187.

Kozlovský O., Balík J., Černý J., Kulhánek M., Kos M., Prášilová M. (2009). Influence of nitrogen fertilizer injection (CULTAN) on yield, yield components formation and quality of winter wheat grain. *Plant, Soil and Environment*. 55 (12), p. 536-543

Koszel M., Kocira A., Lorencowicz E. (2016). The evaluation of the use of biogas plant digestate as fertilizer in alfalfa and spring wheat cultivation. *Fresenius Environmental Bulletin*, 25, p. 3258–3264.

Kunkulberga D., Segliņš V. (2010). Maizes ražošanas tehnoloģija (Bread production technology). Rīga : RTU izdevniecība, p. 53—54. (in latvian)

Li X., Yun S., Zhang C., Fang W., Huang X., Du T. (2018). Application of nano-scale transition metal carbides as accelerants in anaerobic digestion. International Journal of Hydrogen Energy, 43, p.1926–1936.

Ooms N., Delcour J.A. (2019). How to Impact Gluten Protein Network Formation during Wheat Flour Dough *Making. Curr. Opin. Food Sci*. 25:88–97.

Panuccio M.R., Papalia T., Attina E., Giuffre A., Muscolo A. (2018). Use of digestate as an alternative to mineral fertilizer: effects on growth and crop quality. Archives of Agronomy and Soil Science, 65, p. 700–711.

Pitman R. M. (2006). Wood ash uses in forestry – a review of the environmental impacts. Forestry, Vol. 79, p. 563 – 586.

Przygocka-Cyna K., Grzebisz W. (2018). Biogas digestate – benefits and risks for soil fertility and crop quality – an evaluation of grain maize response. Open Chemistry, 16 (1), p. 258-271.

Riva C., Orzi V., Carozzi M., Acutis M., Boccasile G., Lonati S., Tambone F, D'Imporzano G., Adani F. (2016). Short-term experiments in using digestate products as substitutes for mineral (N) fertilizer: agronomic performance, odours, and ammonia emission impacts. *Science of The Total Environment*, 547, p. 206–214.

Różyło K., Gawlik-Dziki U., Swieca M., Różyło R., Pałys E. (2015). Winter wheat fertilized with biogas residue and mining waste - yielding and the quality of grain. *Journal of the Science of Food and Agriculture*, 96 (10), p. 3454–3461.

Sänger A., Geisseler D., Ludwig B. (2014). C and N dynamics of a range of biogas slurries as a function of application rate and soil texture: a laboratory experiment. *Archives of Agronomy and Soil Science*, 60, p.1779–1794. Available: https:10.1080/03650340.2014.907491 (viewed 06.09.2023).

Schröder J., Uenk D., Hilhorst G.J. (2007). Long-term nitrogen fertilizer replacement value of cattle manures applied to cut grassland. Plant Soil, 299, p. 83–99.

Shevkani K., Singh N., Bajaj R., Kaur A. (2017). Wheat starch production, structure, functionality and applications—a review. *International Journal of Food Science & Technology*, 52(1), p. 38-58.

Sørensen P. (2004). Immobilisation, remineralisation and residual effects in subsequent crops of dairy cattle slurry nitrogen compared to mineral fertiliser nitrogen. *Plant Soil*, 267, p. 285–296.

Udall D., Rayns F., Charlesworth S. (2017). The Potential of Biochar and Anaerobic Digestate use in a Temperate Conventional Wheat Production System. *International Journal of Research in Agriculture and Forestry*, 4(10), p. 44-49.

Zariņš Z., Neimane L., Bodnieks E. (2015) Uztura mācība (6. pārstrādātais un papildinātais izd.) (Nutrition education (6th revised and supplemented ed.)). Rīga: LU Akadēmiskais apgāds, p.113. (in latvian)