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Effects of biogas-derived liquid digestates on wheat yield, kernel quality and economic performance under semi-arid conditions

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Abstract

This study evaluated the effects of biogas-derived liquid digestates on wheat yield, yield components, kernel quality, nutrient contents, and economic performance under semi-arid Central Anatolian conditions. Field experiments were conducted using three digestate types—poultry manure + poppy residue (PP), cattle manure + plant waste (CP), and a poultry + cattle mixture (PC)—applied at 15, 30, 45, and 60 t ha⁻¹, alongside control and NPK treatments. Liquid digestates significantly increased kernel yield compared with the control, with clear differences among digestate types and application rates. Under PP, CP, and PC treatments, yield increased from 2195.2 to 2717.9 kg ha⁻¹, from 2352.2 to 2850.9 kg ha⁻¹, and from 2393.7 to 2807.0 kg ha⁻¹, respectively, with maximum values observed at 30 t ha⁻¹. NPK consistently produced high yields (2807.9-2977.1 kg ha⁻¹). Yield components improved under digestate applications. Digestate applications improved several yield-related traits across all digestate types. Harvest index, plant height, spike length, peduncle length, stem + spikelet weight, spikelet kernel number, spikelet kernel weight, and thousand kernel weight generally increased under digestate treatments compared with the control, although the magnitude of response varied according to digestate source and application rate. Kernel quality traits varied moderately, with crude protein (12.94-16.01%), wet gluten (24.73-36.0%), and Zeleny sedimentation (39.0-62.0 mL). Under PP digestate application, K and Ca levels in wheat kernels were significant ($p < 0.01$), whereas CP and PC showed limited effects, with significance observed only for Fe. Multivariate analyses indicated that net income was primarily driven by kernel yield and its components. Economic evaluation showed that digestate applications increased profitability, with the highest net income under CP at 30 t ha⁻¹ (\$955.2 ha⁻¹ yr⁻¹). Although the highest yield and net income were generally obtained around 30 t ha⁻¹, 15 t ha⁻¹ may represent a safer option where salinity risk and long-term soil effects are major concerns. Overall, biogas liquid digestates—especially CP and PC applied at moderate rates—represent effective and economically viable nutrient sources for wheat production in semi-arid systems. However, further multi-year studies are required to assess long-term impacts on soil properties, nutrient dynamics, and environmental sustainability.

Keywords: Soil fertility, anaerobic digestate, wheat kernel yield and quality, economic evaluation, semi-arid conditions.

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Introduction

A growing global population and ongoing climate change are compelling us to reconsider current food production systems. Moreover, the depletion of natural resources, particularly soil and water, necessitates the development of sustainable agricultural practices that minimize environmental degradation (FAO, 2017;



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Rockström et al., 2017). These challenges are especially pronounced in semi-arid regions, where limited water availability and low soil fertility constrain crop production. Under such conditions, improving resource-use efficiency, particularly for water and nutrients, is essential to sustain agricultural productivity (Crespo-Herrera et al., 2018).

Historically, mineral fertilizers have significantly increased crop yields; however, their reliance on fossil fuels, high costs, and adverse environmental impacts—such as greenhouse gas emissions, nutrient losses, and soil degradation—have raised concerns about their long-term sustainability (Sutton et al., 2011; Lal, 2020). Given these limitations, there is a growing need for alternative nutrient management strategies that are both environmentally sustainable and economically viable.

Biogas is a key component of the circular bioeconomy, as it is produced from organic waste and converted into renewable energy through anaerobic digestion (Al Seadi et al., 2013). In addition to biogas, this process generates a liquid by-product known as digestate, which has gained increasing attention as an alternative fertilizer due to its high concentrations of readily available nutrients, particularly ammonium-N, phosphorus, and potassium (Tambone et al., 2010; Möller and Müller, 2012). During anaerobic digestion, organic nitrogen is transformed into ammonium-N, thereby increasing nitrogen availability to plants and enabling more efficient crop production (Möller and Stinner, 2009).

Although digestates have several agronomic benefits, their fertilizer value depends strongly on feedstock composition, anaerobic digestion conditions, retention time, nutrient composition, and post-digestion management (Möller and Müller, 2012; Namlı et al., 2023). Previous studies have shown that digestate applications can improve wheat yield, mainly through the supply of readily available nitrogen (Möller and Stinner, 2009; Hijazi et al., 2020). However, integrated field studies evaluating the simultaneous effects of digestates on yield performance, kernel quality, nutrient accumulation, and economic return under semi-arid conditions remain limited. This gap is particularly important because limited water availability, salinity risk, and nutrient imbalance may strongly influence digestate efficiency in semi-arid environments. Further research is also needed to determine whether excessive digestate application rates may cause salinity stress or nutrient imbalance due to high electrical conductivity and ammonium content (Möller and Müller, 2012).

Therefore, an integrated evaluation of liquid digestate performance is needed, considering crop yield, kernel quality, nutrient accumulation, and economic return under field conditions. Such an approach is particularly important in semi-arid regions, where nutrient availability, salinity risk, and water limitation may strongly affect digestate efficiency.

The aim of this study was to evaluate the effects of biogas-derived liquid digestates from different feedstocks (poultry manure+plant waste, cattle manure+plant waste, and their mixture) on kernel yield, yield components, kernel quality traits, and economic performance of bread wheat (*Triticum aestivum* L.) under semi-arid Central Anatolian conditions. Specifically, the study (i) compared different digestate sources and application rates (15, 30, 45, and 60 t ha⁻¹) to determine their agronomic and quality effects, (ii) identified agronomically and economically optimum application rates, and (iii) evaluated the potential of liquid digestates as sustainable alternatives to mineral fertilization. In addition, multivariate statistical analyses (correlation, principal component analysis, and hierarchical clustering) were applied to examine the relationships among yield, quality traits, nutrient dynamics, and net income, providing an integrated framework for assessing digestate performance in sustainable wheat production systems.

Material and Methods

Experiment location

The field experiment was conducted at the Sarayköy Research and Application Station of the Soil Fertilizer and Water Resources Central Research Institute. The experimental site is located approximately 30 km from Ankara, west of the Ankara–İstanbul highway, on the left bank of the valley stream crossing the Mürted Plain. The average elevation of the site is 894 m above sea level.

Meteorological conditions during the experimental period

Mean temperature, total precipitation, number of rainy days, relative humidity, and wind speed recorded during the 2021 and 2022 growing seasons were used to characterize the climatic conditions of the experimental site (Figure 1). Precipitation was irregular in both years, with higher rainfall generally occurring in spring and early summer, lower rainfall during summer, and increased precipitation toward autumn and winter. Mean temperature reached its maximum values in July and its minimum values during winter. Lower relative humidity and higher wind speed during summer may have increased evapotranspiration. Overall, the climatic conditions reflected the typical pattern of semi-arid regions. According to the Köppen–Geiger climate classification, the research site is located in the cold semi-arid climate zone (BSk) (Köppen, 1900).

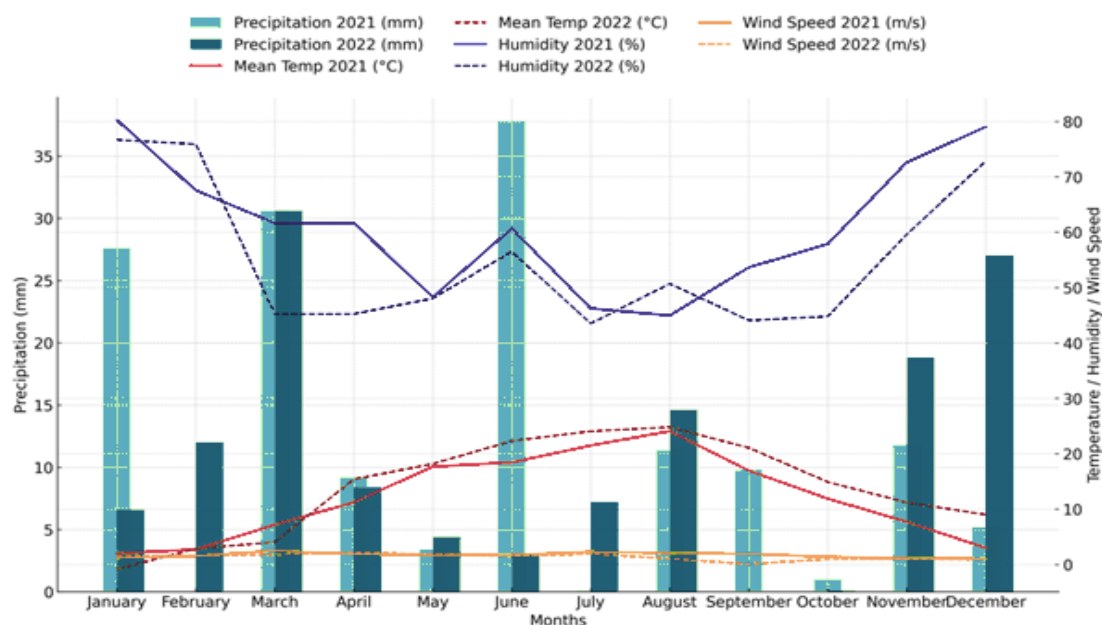


Figure 1. Monthly variation of precipitation (mm), mean air temperature (°C), relative humidity (%), and wind speed (m s^{-1}) during the 2021 and 2022 growing seasons.

Soil properties of the experimental site

The physical and chemical properties of the soil at 0–20 and 20–40 cm depths are presented in Table 1. The experimental soil had a clay texture and a slightly alkaline reaction. Electrical conductivity values were low, indicating non-saline conditions. Soil organic matter content was low and decreased with depth, which is typical of cultivated soils under semi-arid conditions. The soil was moderately calcareous, with relatively uniform CaCO_3 distribution throughout the profile. Available phosphorus and potassium contents were higher in the surface layer than in the subsoil. Bulk density ranged from 1.16 to 1.22 g cm^{-3} , and available water capacity was 16.48% and 16.67% at 0–20 and 20–40 cm depths, respectively. Saturated hydraulic conductivity was low, reflecting limited infiltration and drainage associated with the high clay content. Based on its high clay content and shrink–swell characteristics, the soil was classified as a Vertisol according to USDA Soil Taxonomy.

Table 1. Soil attributes of the experimental area

Soil attributes	0-20 cm	20-40 cm	Soil attributes	0-20 cm	20-40 cm
Electrical conductivity, dS m^{-1}	0.88	0.90	Clay, %	44.7	48.6
PH	7.83	7.74	Texture class	Clay	Clay
Organic matter, %	1.38	0.98	Bulk density, g cm^{-3}	1.22	1.16
CaCO_3 , %	13.1	12.3	Field capacity, %	32.50	36.45
Available P_2O_5 , kg ha^{-1}	54.0	46.0	Permanent wilting point, %	16.02	19.78
Available K_2O , kg ha^{-1}	2450	1800	Available water capacity, %	16.48	16.67
Sand, %	24.3	23.3	Hydraulic conductivity, cm h^{-1}	0.65	0.61
Silt, %	31.0	28.1			

Attributes of biogas liquid digestates used in the field experiment

The chemical properties of the biogas liquid digestates used in the experiment are presented in Table 2. Three digestate types were evaluated: poultry manure + poppy waste (PP), cattle manure + plant waste (CP), and a mixture of poultry and cattle manure (PC). Organic matter percentages ranged between 1.73% and 4.60%, with PP having the highest value. The digestates were neutral to alkaline, with pH values ranging from 7.36 to 8.65, and had high electrical conductivity values (23.0–37.4 dS m^{-1}), indicating high soluble salt contents. Total N, P, and K contents varied among digestate types and ranged from 0.56% to 0.86%, 1.20% to 1.86%, and 0.40% to 0.47%, respectively. Water-soluble P_2O_5 and K_2O contents ranged from 0.53% to 0.79% and from 0.32% to 0.37%, respectively. The total content of humic acids and fulvic acid ranged between 3.93% and 6.10%, with the most humic/fulvic acids present in the PC material. The calcium (Ca) and magnesium (Mg) nutrients were generally at low concentrations (0.29 - 0.49% and 0.01 - 0.09%, respectively). Trace element concentrations (Fe, B) were all generally low and within permissible limits, as Co and Pb had less than detectable levels. Overall, the digestates contained considerable amounts of nutrients and organic matter, but their high salinity highlights the need for appropriate application rates and careful management to ensure safe and effective agricultural use (Alaboz et al., 2021; Namlı et al., 2023).

Table 2. Attributes of biogas liquid digestates used in field experiment

Attributes	Biogas liquid digestates		
	PP	CP	PC
Organic matter, %	4.60	1.73	3.68
PH	8.11	8.65	7.36
Electrical conductivity, dS m ⁻¹	37.4	23.0	24.0
Total N, %	0.86	0.56	0.58
Total K, %	0.47	0.40	0.42
Total P, %	1.55	1.20	1.86
Water soluble P ₂ O ₅ , %	0.65	0.53	0.79
Water soluble K ₂ O, %	0.37	0.32	0.35
Total humic and fulvic acid, %	3.93	5.25	6.10
Total Ca, %	0.49	0.36	0.29
Total Mg, %	0.02	0.01	0.09
Total Fe, mg kg ⁻¹	1370.00	1320.00	1350.00
Total Cu, mg kg ⁻¹	25.0	14.00	10.00
Total Mn, mg kg ⁻¹	32.00	39.25	26.20
Total Zn, mg kg ⁻¹	36.0	UDL	10.0
Total B, mg kg ⁻¹	30.0	8.00	10.0
Total Ni, mg kg ⁻¹	3.30	UDL	4.00
Total Cd, mg kg ⁻¹	1.67	1.67	1.60
Total Co, mg kg ⁻¹	UDL	UDL	UDL
Total Cr, mg kg ⁻¹	1.34	5.08	2.00
Total Pb, mg kg ⁻¹	UDL	UDL	UDL

PP: Liquid digestate from poultry waste + plant (poppy) waste, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste, pH: Soil reaction, UDL: Under the detection limit

Methods

Field experiment subjects and experimental design

The field study evaluated three liquid digestate sources: poultry manure + poppy residue (PP), cattle manure + plant waste (CP), and a poultry + cattle manure mixture (PC). For each digestate source, six treatments were established: an unfertilized control, an optimum mineral fertilization treatment (NPK: 80 kg N ha⁻¹ + 40 kg P₂O₅ ha⁻¹), and four digestate application rates: 15, 30, 45, and 60 t ha⁻¹.

The application rates (15, 30, 45, and 60 t ha⁻¹) were selected based on a combination of (i) commonly reported digestate application ranges in the literature, (ii) regional agronomic practices, and (iii) the need to evaluate both agronomically optimal and potentially excessive application levels under field conditions. Previous studies have shown that liquid digestates are typically applied within a wide range (approximately 10–60 t ha⁻¹), depending on their nutrient content and soil characteristics (Möller and Müller, 2012; Nkoa, 2014). Accordingly, the lower and moderate rates (15 and 30 t ha⁻¹) were chosen to represent practical and potentially optimal agronomic applications, while the higher rates (45 and 60 t ha⁻¹) were included to assess possible negative effects associated with high EC, salinity, and ammonium (NH₄⁺) load. This approach allowed us to capture the dose–response relationship and to identify a threshold beyond which the benefits of nutrient supply may be offset by physicochemical constraints. Mineral fertilization (NPK) was included as a reference to represent optimum fertilization under regional agronomic conditions. Since the nutrient composition of liquid digestates varies depending on feedstock and production conditions, a strict nutrient equivalence approach was not applied. Therefore, comparisons were based on agronomic performance rather than exact nutrient matching. Separate experiments were established for each digestate source; thus, three independent experiments were conducted. Each of these experiments included six treatments within its own structure. In all three experiments, a randomized complete block design with three replications was used. Each liquid digestate experiment consisted of 18 plots (6 treatments × 3 replications), and the entire study comprised a total of 54 plots. The control and NPK treatments were repeated separately within each digestate source.

The liquid digestates used in the study were obtained from three different biogas facilities and differed in feedstock composition and chemical characteristics. The PP liquid fermented product was obtained from a biogas facility located in Afyon province, Türkiye, while the CP liquid fermented product was obtained from Aksaray province. The PC liquid fermented product was collected from a private biogas plant in the Polatlı district of Ankara province. Liquid fermented products obtained from three different biogas facilities were uniformly applied to the plots on October 12, 2021. The Bayraktar 2000 wheat variety was sown on November 1, 2021, at the Sarayköy Research and Application Station (Kahramankazan, Ankara, Türkiye). The experiment covered a single growing season and was conducted between November 1, 2021, and July 7, 2022. The

experiment was arranged in a randomized block design with three replications. The plot dimensions were 3 m in width and 10 m in length, corresponding to a total plot area of 30 m². To minimize edge effects, a 0.5 m border was left on all sides, resulting in a harvest area of 18 m². Liquid digestates were uniformly applied to the soil surface of each plot at the specified rates (t ha⁻¹) prior to sowing and then incorporated into the topsoil (0 - 15 cm) to ensure homogeneous distribution. All applications were transported to each plot using a tanker and were carried out manually with calibrated containers to ensure accurate dosing for each treatment.

In this study, wheat was grown under rainfed (dryland) conditions. No fertilizer or digestate was applied in the control plots, whereas in the NPK treatment, fertilization was carried out based on soil analysis results. Optimum NPK fertilization was applied at rates of 80 kg N ha⁻¹ and 40 kg P₂O₅ ha⁻¹. One-third of the nitrogen fertilizer was applied at sowing, and the remaining two-thirds were applied at the tillering stage; P was applied as a basal fertilizer. Wheat was harvested on July 7, 2022.

Soil analysis

Soil samples were collected from two depths, 0–20 and 20–40 cm, during the experimental period for analysis. Soil pH and EC were measured following [Richards \(1954\)](#). The content of organic matter was assessed using the modified Walkley and Black method ([Walkley and Black, 1934](#)). Available P₂O₅ and K₂O were analyzed using sodium bicarbonate and ammonium acetate extraction methods, respectively ([Olsen and Dean, 1965](#); [Pratt, 1965](#)). For the determination of calcium carbonate content, a Scheibler calcimeter was used ([Soil Survey Staff, 2014](#)), and soil texture was characterized by the hydrometer method ([Bouyoucos, 1951](#)). Field capacity (FC), permanent wilting point (PWP), and available water capacity (AWC) were determined as per [Hillel \(1982\)](#). The bulk density (BD) was determined following [Blake and Hartge \(1986\)](#), and saturated hydraulic conductivity (Ks) measurements were taken according to established methods ([US Salinity Laboratory Staff, 1954](#)).

Analytical methods for biogas liquid digestates

The chemical properties of the biogas liquid digestates were determined using standard analytical procedures. Organic matter content was measured according to the Walkley–Black wet oxidation method ([Walkley and Black, 1934](#)). The pH and EC of the digestates were determined in aqueous extracts following standard procedures described by [APHA \(2017\)](#). Total N content was analyzed using the Kjeldahl digestion method as described by [Bremner \(1996\)](#). Total P content was determined colorimetrically using the molybdenum blue method according to [Murphy and Riley \(1962\)](#). Total K was measured using standard procedures outlined by [AOAC \(2005\)](#). Water-soluble P₂O₅ and K₂O fractions were extracted and quantified according to [AOAC \(2005\)](#) methods. Humic and fulvic acid contents were determined following the fractionation procedures described by [Swift \(1996\)](#). Total Ca, Mg, and micronutrient elements (Fe, Cu, Mn, Zn, B, Ni, Cd, Cr, Co, and Pb) were determined using inductively coupled plasma–optical emission spectrometry (ICP-OES) according to EPA Method 3051A ([EPA, 2007](#)).

Wheat yield and yield components

Wheat yield and yield components were determined from ten randomly selected plants and spikes per plot at harvest. Kernel yield (kg ha⁻¹) was calculated on a hectare basis following standard procedures ([ASAE, 2003](#)). Harvest index (HI) was computed as the ratio of grain yield to total above-ground biomass ([Donald and Hamblin, 1976](#)). Plant height (WPH), spike length (SL), and peduncle length (PL) were measured according to standard phenotyping protocols ([ICARDA, 2019](#)). Yield components, including spikelet kernel number (SKN), spikelet kernel weight (SKW), and thousand kernel weight (TKW), were determined using standard methods ([ICC, 1994](#)). Grain quality traits, including test weight, hardness index, gluten characteristics (wet gluten, dry gluten, gluten index), and sedimentation values (ZS and MZS), were analyzed according to [ISO 5529:2007](#), [ICC \(1994\)](#), and [AACC \(2010\)](#) standard methods. Total N content was determined using the Dumas combustion method ([AOAC, 1995](#)), and crude protein (PR) content was calculated using a conversion factor of 5.70 ([AACC, 2010](#)).

Quality traits and macro-micro nutrient contents in wheat kernel

Phosphorus concentration in wheat kernels was determined colorimetrically after digestion ([Kacar, 2014](#)). Total K, Ca, Mg, Fe, B, Cu, Mn, and Zn concentrations were determined using ICP-OES ([EPA, 2007](#)). Total N was determined using the Dumas combustion method, as described above.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics 25.0 (IBM Corp., Armonk, NY, USA). The experiment was arranged as a randomized complete block design with three replications, and the experimental unit was a plot. Because the three digestate sources were established as separate but parallel experiments, treatment effects were first analyzed separately for each digestate source using one-way ANOVA,

with application rate as the main factor. In addition, combined mean comparisons were performed where overall comparisons among digestate sources and application rates were presented. The assumptions of normality and homogeneity of variance were tested using the Shapiro–Wilk and Levene’s tests, respectively. When significant differences were detected, mean comparisons were performed using Duncan’s multiple range test at $P < 0.05$ or $P < 0.01$.

Multivariate analyses were conducted to examine relationships among variables. Principal component analysis (PCA) was performed using OriginPro 2025b (OriginLab Corporation, USA). Prior to PCA, descriptive statistics were examined to evaluate data distribution and variability. The suitability of the dataset for PCA was assessed using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett’s test of sphericity. The KMO value was found to be 0.729, indicating good sampling adequacy. Bartlett’s test of sphericity was significant ($\chi^2 = 376.456$, $p < 0.001$), confirming that the dataset was suitable for PCA. PCA was then performed using Varimax (orthogonal) rotation to improve the interpretability of the components. In addition, Pearson correlation analysis and hierarchical clustering were conducted, and the results were visualized using correlation matrices and heat maps generated in OriginPro 2025b.

Economic evaluation

Economic analysis was performed separately for each treatment. Gross income was calculated from kernel yield and wheat sale price. Net return was calculated by subtracting total production costs from gross income. Variable and fixed costs for the study period were adopted from Inan (2008).

Results

Effects of liquid digestate on wheat yield and yield traits

Analysis of variance showed that digestate application rate significantly affected wheat yield and most yield components. However, thousand kernel weight (TKW) was not significantly affected in the PP and CP digestate treatments, whereas it was significant in the PC treatment (Table 3). Additionally, for most spike yield components, PC and CP produced stronger responses than did PP. Digestate applications significantly increased kernel yield compared with the control; however, yield generally plateaued or slightly declined at higher application rates, particularly above 30 t ha^{-1} (Figure 2). Overall, the highest mean yield was obtained under NPK, followed by the moderate digestate application rates.

Table 3. Variance analysis of biogas liquid digestate on wheat yield and yield parameters in field experiment (Kahramankazan, Ankara, Türkiye)

LDs	Source of Variance	Yield	HI	WPH	SL	PL	SSW	SKN	SKW	TKW
PP	F value	7.707	664.616	52.861	554.199	82.478	20.032	129.446	108.438	2.125
	p value	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.145
	Significance	**	**	**	**	**	**	**	**	ns
	CV, %	8.72	7.09	4.80	4.82	8.68	3.66	8.44	4.89	7.09
CP	F value	3.365	438.337	92.791	12.943	60.541	13.596	89.220	344.390	3.240
	p value	0.048	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.054
	Significance	*	**	**	**	**	**	**	**	ns
	CV, %	8.73	6.92	4.61	5.61	8.12	2.63	8.02	4.91	3.12
PC	F value	3.546	423.908	164.203	798.709	85.970	22.298	188.739	301.120	4.150
	p value	0.042	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.027
	Significance	*	**	**	**	**	**	**	**	*
	CV, %	8.84	7.02	4.79	4.73	8.56	3.89	7.76	5.07	4.41

LDs: Biogas liquid digestates, PP: Liquid digestate from poultry waste + plant (poppy) waste, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste, HI: Harvest index, WPH: Wheat plant height, SL: Spike length, PL: Peduncle length, SSW: Stem+spikelet weight, SKN: Spikelet kernel number, SKW: Spikelet kernel weight, TKW: Thousand kernel weight. ** significant at $p < 0.01$; *significant at $p < 0.05$; ns, nonsignificant

The effects of biogas liquid digestate applications on wheat kernel yield and yield traits under field conditions are presented in Table 4. The highest grain yield across the three digestate types was generally obtained under NPK and moderate application rates, whereas the lowest values were recorded in the control treatments. In PP, the highest yield was 2977.1 (NPK) and the lowest was 2195.2 (control) ; in CP, the highest was $2850.9 \text{ (30 t ha}^{-1}\text{)}$ and the lowest was 2352.2 (control) ; and in PC, the highest was 2852.6 (NPK) and the lowest was 2393.7 (control) . The HI reached its highest values mostly at higher application rates (PP: 49.27 ; CP: 49.59 ; PC: 49.55 at 60 t ha^{-1}) and its lowest values under control conditions (40.20 – 40.82 – 40.64). Plant height, spike length, and peduncle length were highest under NPK and lowest under control treatments. Stem + spike weight, spikelet kernel number, and spikelet kernel weight generally reached maximum values at moderate to high application rates (30 – 45 t ha^{-1}), while minimum values were observed under control conditions. TKW

generally followed a similar pattern, with higher values observed under NPK and low-to-moderate application rates, while excessive application rates resulted in slight reductions.

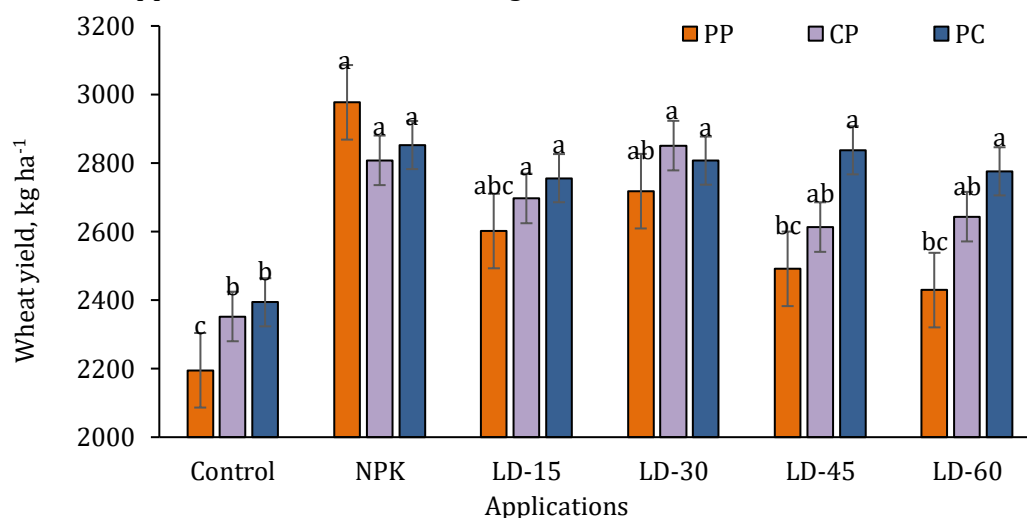


Figure 2. Effects of control, NPK, and different liquid digestate doses on wheat yield under field conditions. PP: liquid digestate from poultry waste + plant (poppy) waste; CP: liquid digestate from cattle waste + plant waste; PC: liquid digestate from poultry waste + cattle waste; NPK: optimum mineral fertilization; Control: no fertilizer or liquid digestate application; LD-15, LD-30, LD-45, and LD-60: liquid digestate applications at 15, 30, 45, and 60 t ha⁻¹, respectively.

Table 4. The effect of biogas liquid digestates application on yield and yield traits of wheat in field experiment (Kahramankazan, Ankara, Türkiye)

LDs	Applications	Yield	HI	WPH	SL	PL	SSW	SKN	SKW	TKW
PP	Control	2195.2 c	40.20 b	65.10 d	8.85 b	31.53 d	0.35 b	29.90 d	1.27 e	30.11
	NPK	2977.1 a	49.25 a	75.24 a	9.54 a	41.64 a	0.38 a	37.00 b	1.48 a	28.16
	15 t ha ⁻¹	2601.7 abc	48.65 a	70.64 c	8.14 d	38.73 b	0.38 a	33.60 c	1.37 d	28.33
	30 t ha ⁻¹	2717.9 ab	48.81 a	72.69 bc	8.63 c	38.45 b	0.39 a	36.70 b	1.41 bc	27.32
	45 t ha ⁻¹	2491.2 bc	48.69 a	74.18 ab	8.90 b	38.92 b	0.39 a	38.61 a	1.43 b	26.82
	60 t ha ⁻¹	2429.2 bc	49.27 a	71.65 c	8.82 b	36.22 c	0.39 a	34.63 c	1.39 cd	28.25
CP	Control	2352.2 b	40.82 b	65.27 e	8.84 b	31.78 d	0.36 b	30.27 d	1.26 e	32.55
	NPK	2807.9 ab	49.45 a	74.81 a	9.54 a	41.21 a	0.38 a	37.07 b	1.48 a	32.74
	15 t ha ⁻¹	2696.7 ab	49.41 a	70.52 d	8.12 c	38.75 b	0.38 a	33.90 c	1.37 d	31.98
	30 t ha ⁻¹	2850.9 a	49.37 a	72.80 bc	8.64 bc	38.01 bc	0.38 a	36.63 b	1.41 bc	30.75
	45 t ha ⁻¹	2613.1 ab	49.45 a	74.27 ab	9.22 ab	38.66 b	0.39 a	38.73 a	1.42 b	32.17
	60 t ha ⁻¹	2643.6 ab	49.59 a	72.10 cd	8.80 b	36.50 c	0.39 a	35.17 c	1.39 c	31.10
PC	Control	2393.7 b	40.64 b	65.50 e	8.85 b	31.54 d	0.35 b	30.57 e	1.25 e	32.53 a
	NPK	2852.6 a	49.36 a	75.62 a	9.56 a	41.66 a	0.38 a	37.00 b	1.48 a	32.71 a
	15 t ha ⁻¹	2755.9 a	49.13 a	71.24 d	8.18 d	38.68 b	0.38 a	33.70 d	1.37 d	31.85 a
	30 t ha ⁻¹	2807.0 a	49.49 a	72.75 c	8.66 c	38.49 b	0.39 a	36.73 b	1.41 bc	30.89 ab
	45 t ha ⁻¹	2837.2 a	49.39 a	74.09 b	8.89 b	38.69 b	0.39 a	38.67 a	1.41 b	30.75 ab
	60 t ha ⁻¹	2775.8 a	49.55 a	74.38 ab	8.90 b	36.81 c	0.39 a	35.03 c	1.39 c	29.68 b

LDs: Biogas liquid digestates, PP: Liquid digestate from poultry waste + plant (poppy) waste, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste, NPK: Optimum fertilization, HI: Harvest index, WPH: Wheat plant height, SL: Spike length, PL: Peduncle length, SSW: Stem+spikelet weight, SKN: Spikelet kernel number, SKW: Spikelet kernel weight, TKW: Thousand kernel weight. Values followed by different uppercase letters within the same column indicate significant differences among biogas liquid digestates (PP, CP, and PC) according to Duncan's multiple range test ($P < 0.01$). Values followed by different lowercase letters within the same column indicate significant differences among treatments according to Duncan's multiple range test.

Table 5 presents the results of the analysis of variance on the effects of biogas liquid digestates on wheat quality parameters. When digestate types were evaluated separately, only the ZS parameter was found to be statistically significant ($p < 0.05$) in the PP digestate, while no significance was observed for the other parameters. In the CP digestate, only the GI parameter was significant ($p < 0.05$), whereas all other parameters were statistically non-significant. In the PC digestate, significant differences were observed for PR, D-SKCS, WG, ZS, and MZS parameters ($p < 0.05$), while no significant effects were found for the remaining parameters. Overall, the table indicates that variations in quality parameters depend on both digestate type and application rate, and that these effects vary depending on the specific parameter.

Table 5. Variance analysis of biogas liquid digestate on wheat quality traits in field experiment (Kahramankazan, Ankara, Türkiye)

LDs	Source of Variance	PR	HW	H-SKCS	D-SKCS	WG	DG	GI	ZS	MZS
PP	F value	2.481	0.614	1.499	1.252	2.289	1.680	2.604	3.523	1.138
	p value	0.104	0.692	0.274	0.355	0.124	0.227	0.093	0.043	0.402
	Significance	ns	ns	ns	ns	ns	ns	ns	*	ns
	CV, %	6.91	2.02	3.46	5.69	9.18	9.36	3.11	13.00	9.60
CP	F value	0.803	1.513	1.376	1.125	0.772	1.059	3.522	1.259	0.859
	p value	0.572	0.269	0.311	0.407	0.591	0.437	0.043	0.353	0.540
	Significance	ns	ns	ns	ns	ns	ns	*	ns	ns
	CV, %	3.25	0.71	3.28	2.60	12.19	8.17	2.13	9.45	10.80
PC	F value	4.804	1.890	0.808	5.222	4.543	1.677	0.784	3.406	4.433
	p value	0.017	0.183	0.569	0.013	0.020	0.227	0.584	0.047	0.022
	Significance	*	ns	ns	*	*	ns	ns	*	*
	CV, %	3.42	1.06	2.32	3.01	5.15	10.63	1.63	7.59	10.66

LDs: Biogas liquid digestates, PP: Liquid digestate from poultry waste + plant (poppy) waste, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste, PR: Crude protein, HW: Hectoliter weight, H-SKCS: Hardness-Single Kernel Characterization System, D-SKCS: Diameter- Single Kernel Characterization System, WG: Wet gluten, DG: Dry gluten, GI: Gluten index, ZS: Zeleny sedimentation, MZS: Modified zeleny sedimentation. ** significant at $p < 0.01$; *significant at $p < 0.05$; ns, nonsignificant

Wheat quality traits varied widely depending on the source of the digestate used and the rate at which it was applied (Table 6). In PP, significant differences among applications were observed only for ZS, with the lowest value recorded in the control (46.00) and the highest at 45 t ha^{-1} (62.00). In CP, significant differences among applications were found for GI, with the lowest value at 15 t ha^{-1} (93.70) and the highest at 60 t ha^{-1} (98.29). In PC, significant differences among applications were observed for PR, D-SKCS, WG, ZS, and MZS. PR ranged from 12.94 (control) to 14.01 (60 t ha^{-1}); D-SKCS from 28.53 (60 t ha^{-1}) to 30.70 (NPK); WG from 26.98 (control) to 30.23 (60 t ha^{-1}); ZS from 39.00 (control) to 46.33 (60 t ha^{-1}); and MZS from 32.00 (30 t ha^{-1}) to 41.00 (60 t ha^{-1}). PP digestate was more closely associated with protein- and gluten-related traits, whereas CP and PC digestates generally showed relatively higher values for physical grain properties. In terms of kernel hardness, PP tends to exhibit higher values compared to CP and PC. The gluten index shows a similar range across all digestates and does not display a distinct difference. Overall, PP digestate was more strongly associated with protein and gluten characteristics, whereas CP and PC digestates were more closely related to physical grain traits.

Table 6. The effect of biogas liquid digestates application on wheat quality traits in field experiment (Kahramankazan, Ankara, Türkiye)

LDs	Applications	PR	HW	H-SKCS	D-SKCS	WG	DG	GI	ZS	MZS
PP	Control	13.76	78.56	11.86	28.43	30.05	10.12	98.29	46.00 c	43.00
	NPK	14.98	77.98	12.03	27.59	34.48	11.55	95.35	53.00 abc	45.00
	15 t ha^{-1}	14.85	77.52	12.69	27.91	32.93	11.13	96.14	52.33 bc	42.67
	30 t ha^{-1}	14.89	77.20	11.97	26.33	34.28	11.72	97.10	51.00 bc	45.00
	45 t ha^{-1}	16.01	77.11	12.10	26.79	36.00	12.05	93.43	62.00 a	49.67
	60 t ha^{-1}	15.60	77.92	12.25	27.61	35.30	11.90	94.03	56.33 ab	44.00
CP	Control	13.21	80.47	11.07	29.69	28.18	9.40	98.25 a	40.33	37.00
	NPK	13.80	80.69	11.20	30.42	29.32	9.87	97.00 a	43.67	40.33
	15 t ha^{-1}	13.55	80.59	11.77	30.61	24.73	10.55	93.70 b	42.67	37.00
	30 t ha^{-1}	13.85	80.28	11.38	29.50	29.58	9.95	97.98 a	46.67	42.33
	45 t ha^{-1}	13.41	80.47	11.31	30.05	29.10	9.77	97.65 a	42.33	37.33
	60 t ha^{-1}	13.51	79.60	11.48	30.17	27.52	9.23	98.29 a	39.33	36.33
PC	Control	12.94 b	80.05	11.08	30.41 ab	26.98 c	9.25	96.91	39.00 c	36.33 ab
	NPK	13.50 a	80.79	11.21	30.70 a	28.05 bc	9.73	96.58	43.67 ab	38.33 a
	15 t ha^{-1}	13.49 a	79.96	10.84	29.62 abc	28.17 bc	9.57	97.70	42.67 abc	39.33 a
	30 t ha^{-1}	13.46 a	79.85	11.17	29.27 bc	29.12 ab	9.73	95.50	41.33 bc	32.00 b
	45 t ha^{-1}	13.73 a	79.25	11.07	29.22 c	29.73 ab	10.03	95.75	43.67 ab	39.00 a
	60 t ha^{-1}	14.01 a	79.34	11.03	28.53 c	30.23 a	11.27	95.54	46.33 a	41.00 a

LDs: biogas liquid digestates; PP: liquid digestate from poultry waste + plant (poppy) waste; CP: liquid digestate from cattle waste + plant waste; PC: liquid digestate from poultry waste + cattle waste; NPK: optimum mineral fertilization; PR: crude protein; HW: hectoliter weight; H-SKCS: hardness-single kernel characterization system; D-SKCS: diameter-single kernel characterization system; WG: wet gluten; DG: dry gluten; GI: gluten index; ZS: Zeleny sedimentation; MZS: modified Zeleny sedimentation. Values followed by different lowercase letters within the same column and within each digestate source indicate significant differences among treatments according to Duncan's multiple range test at $P < 0.05$.

Effects of liquid digestate on macro and micro nutrient contents in wheat kernel

Analysis of variance showed that the effects of liquid digestates on macro- and micronutrient contents in wheat kernels were element-specific (Table 7). When different digestate types were evaluated separately, K and Ca levels in wheat kernels were found to be significant ($p < 0.01$) under the PP digestate application. The CP and PC digestates were generally found to have limited effects on nutrient levels, showing significance only for Fe. Overall, this indicates that changes in nutrient accumulation resulting from digestate application are not consistent across different elements.

Table 7. Variance analysis of biogas liquid digestate on macro and micro nutrient contents in wheat kernel in field experiment (Kahramankazan, Ankara, Türkiye)

LDs	Source of Variance	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total Fe (ppm)	Total B (ppm)
PP	F value	0.995	0.868	6.661	7.712	0.881	1.173	2.217
	p value	0.467	0.535	0.006	0.003	0.528	0.387	0.133
	Significance	ns	ns	**	**	ns	ns	ns
	CV, %	7.66	3.16	1.66	2.79	4.65	7.04	15.15
CP	F value	1.630	0.860	0.567	1.422	1.115	5.672	3.023
	p value	0.239	0.540	0.724	0.297	0.411	0.012	0.064
	Significance	ns	ns	ns	ns	ns	*	ns
	CV, %	7.13	2.97	12.82	8.81	3.82	7.93	10.47
PC	F value	0.299	3.129	0.373	2.436	0.532	6.454	0.971
	p value	0.903	0.059	0.856	0.108	0.748	0.006	0.480
	Significance	ns	ns	ns	ns	ns	**	ns
	CV, %	7.17	2.65	9.17	8.09	3.56	6.74	8.55

LDs: Biogas liquid digestates, PP: Liquid digestate from poultry waste + plant (poppy) waste, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste. ** significant at $p < 0.01$; * significant at $p < 0.05$; ns, nonsignificant

The effects of digestate applications on kernel nutrient contents are presented in Table 8. Fe was the most responsive element; significant differences among application rates were observed particularly in the PC and CP digestates, with the highest values recorded under PC. In the PP digestate, K and Ca showed significant differences among application rates. Fe exhibited a variation range of 41.60–49.33 ppm in the PC digestate and 39.40–47.51 ppm in the CP digestate. In the PP digestate, K ranged between 0.18% and 0.24%, while Ca varied from 0.41% to 0.74%. N, P, Mg, and B generally showed limited variation and were mostly not significantly affected. Overall, nutrient responses were element-specific, and no consistent trend was observed across all nutrients.

Table 8. The effect of biogas liquid digestates application on macro and micro nutrient contents in wheat kernel in field experiment (Kahramankazan, Ankara, Türkiye)

LDs	Applications	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total Fe (ppm)	Total B (ppm)	Total Cu (ppm)	Total Mn (ppm)	Total Zn (ppm)
PP	Control	3.39	0.17	0.18 b	0.41 b	0.93	41.40	31.53	UDL	UDL	UDL
	NPK	3.61	0.18	0.24 a	0.44 b	0.95	45.87	39.13	UDL	UDL	UDL
	15 t ha ⁻¹	3.18	0.15	0.18 b	0.74 a	0.91	44.40	39.40	UDL	UDL	UDL
	30 t ha ⁻¹	3.56	0.21	0.21 ab	0.42 b	0.90	45.07	32.00	UDL	UDL	UDL
	45 t ha ⁻¹	3.42	0.22	0.24 a	0.47 b	0.92	44.47	33.53	UDL	UDL	UDL
	60 t ha ⁻¹	3.39	0.18	0.20 ab	0.48 b	0.89	47.07	32.00	UDL	UDL	UDL
CP	Control	3.50	0.20	0.19	0.43	0.91	40.90 b	33.47	UDL	UDL	UDL
	NPK	3.74	0.17	0.21	0.46	0.92	47.51 a	36.60	UDL	UDL	UDL
	15 t ha ⁻¹	3.25	0.19	0.21	0.47	0.94	39.40 b	39.93	UDL	UDL	UDL
	30 t ha ⁻¹	3.62	0.17	0.19	0.42	0.91	43.80 ab	32.87	UDL	UDL	UDL
	45 t ha ⁻¹	3.60	0.14	0.18	0.40	0.88	39.80 b	34.07	UDL	UDL	UDL
	60 t ha ⁻¹	3.40	0.19	0.19	0.43	0.93	42.13 ab	35.74	UDL	UDL	UDL
PC	Control	3.49	0.16	0.20	0.40	0.91	41.60 b	34.07	UDL	UDL	UDL
	NPK	3.39	0.18	0.21	0.43	0.92	47.27 a	35.67	UDL	UDL	UDL
	15 t ha ⁻¹	3.41	0.16	0.20	0.42	0.94	47.60 a	38.47	UDL	UDL	UDL
	30 t ha ⁻¹	3.23	0.22	0.20	0.46	0.91	49.33 a	37.80	UDL	UDL	UDL
	45 t ha ⁻¹	3.45	0.14	0.21	0.46	0.90	48.93 a	36.93	UDL	UDL	UDL
	60 t ha ⁻¹	3.33	0.17	0.19	0.46	0.91	46.40 ab	39.00	UDL	UDL	UDL

LDs: Biogas liquid digestates, PP: Liquid digestate from poultry waste + plant (poppy) waste, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste, NPK: Optimum fertilization. Values followed by different uppercase letters within the same column indicate significant differences among biogas liquid digestates (PP, CP, and PC) according to Duncan's multiple range test ($P < 0.01$). Values followed by different lowercase letters within the same column indicate significant differences among treatments according to Duncan's multiple range test. UDL: Under the detection limit

Effects of liquid digestate on economic analysis

Economic analysis showed that liquid digestate applications increased net returns from wheat production compared with the control treatments (Table 9). However, economic outcomes varied depending on both digestate source and application rate. Moderate application rates provided the highest economic returns relative to input cost; however, higher application rates decreased profitability due to increased input costs. CP and PC digestates were more economically advantageous than PP under the experimental conditions. Overall, liquid digestates increased economic benefits when applied at appropriate rates, with moderate application rates providing the highest net returns.

Table 9. Comparative assessment of the economic analysis under biogas liquid digestate applications (Kahramankazan, Ankara, Türkiye)

Liquid digestates	Applications	Wheat production costs, \$ ha ⁻¹ (1)	Wheat yield, kg ha ⁻¹ (2)	Wheat sales price, \$ kg ⁻¹ (3)	Gross income per ha, \$ ha ⁻¹ year ⁻¹ 4 (2x3)	Net income, \$ ha ⁻¹ year ⁻¹ 5 (4-1)
PP	Control	191.7	2095.2	0.41	859.0	667.3
	NPK	315.1	2977.1	0.41	1220.6	905.6
	15 t ha ⁻¹	202.7	2601.7	0.41	1066.7	864.0
	30 t ha ⁻¹	213.7	2717.9	0.41	1114.3	900.6
	45 t ha ⁻¹	224.7	2491.2	0.41	1021.4	796.7
	60 t ha ⁻¹	235.7	2429.2	0.41	996.0	760.3
CP	Control	191.7	2152.2	0.41	882.4	690.7
	NPK	315.1	2807.9	0.41	1151.2	836.2
	15 t ha ⁻¹	202.7	2696.7	0.41	1105.6	902.9
	30 t ha ⁻¹	213.7	2850.9	0.41	1168.9	955.2
	45 t ha ⁻¹	224.7	2613.1	0.41	1071.4	846.7
	60 t ha ⁻¹	235.7	2643.6	0.41	1083.9	848.2
PC	Control	191.7	2013.7	0.41	825.6	633.9
	NPK	315.1	2852.6	0.41	1169.6	854.5
	15 t ha ⁻¹	202.7	2755.9	0.41	1129.9	927.2
	30 t ha ⁻¹	213.7	2807.0	0.41	1150.9	937.2
	45 t ha ⁻¹	224.7	2837.2	0.41	1163.3	938.5
	60 t ha ⁻¹	235.7	2775.8	0.41	1138.1	902.4

PP: Liquid digestate from poultry waste + plant (poppy) waste, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste, NPK: Optimum fertilization. Values followed by different uppercase letters within the same column indicate significant differences among biogas liquid digestates (PP, CP, and PC) according to Duncan's multiple range test ($P < 0.01$). Values followed by different lowercase letters within the same column indicate significant differences among treatments according to Duncan's multiple range test.

Discussion

Effects of liquid digestate on wheat yield and yield traits

Anaerobic digestion increases the proportion of mineral N in digestates, allowing them to provide readily available nutrients for plant growth and yield formation (Möller and Müller, 2012; Nkoa, 2014). However, digestates may also contain high concentrations of soluble salts and ammonium, which can induce osmotic or ionic stress under certain conditions (Walsh et al., 2018). Therefore, agronomic responses to digestate application should be interpreted as the balance between nutrient supply and potential physicochemical constraints, particularly salinity and ammonium loading.

Under the conditions of this study, selected liquid digestate treatments produced wheat grain yields comparable to those obtained with conventional mineral fertilization (Alburquerque et al., 2012; Barłóg et al., 2020). However, the relationship between digestate application rate and wheat yield was non-linear. Moderate application rates of the liquid digestate resulted in increased wheat yield and yield trait production, indicating the nutrient availability in the liquid digestate matched that of crop nutrient demand. Conversely, high application rates of liquid digestate resulted in decreased wheat yield and yield trait production; this low performance may be attributed to high EC and salinity stress, and the excessive supply of NH_4^+ ions leading to nutrient imbalances and dysfunction of the root system (Nkoa, 2014; Walsh et al., 2018). The yield increases observed at moderate digestate rates were likely associated with improved nutrient availability during critical growth stages, which enhanced assimilate production and partitioning. The lower yield at higher levels of fertilization could indicate a source-sink imbalance in the crop, where the increasing number of kernels is reducing the amount of assimilate available to any grain, a known response in the physiology of wheat (Barłóg et al., 2020).

Differences among digestate types were related to feedstock composition, which influenced nutrient balance, pH, and electrical conductivity (Tambone et al., 2009; Bachmann et al., 2016; Namli et al., 2023). While this study provides valuable information about the use of digestate for agricultural purposes, the results should be viewed within the confines of several limitations. One limitation is that the experiment was conducted during only one growing season and at a single field location. Therefore, the results reflect the short-term and site-specific conditions at the location. Another potential limitation is that the high EC values of the digestates suggest a potential hazard associated with salinity of the soil, especially with repeated or heavy applications. Long-term repeated applications may produce different outcomes in terms of salt accumulation and plant-soil interactions. Another limitation is that long-term changes in soil properties, such as soil organic matter, nutrient accumulation, and soil microbial communities, could not be assessed within the scope of this study. The study also did not assess the variability of climatic conditions between years, thereby affecting its ability to generalize its findings.

Based on the limitations imposed by the existing data, the results presented in this study indicate that liquid digestates can serve as an acceptable source of nutrients when used at moderate application rates and keeping in mind their chemical properties. The benefits observed in this study should be interpreted cautiously, because the experiment was conducted at a single site and during one growing season. Adequate management of application rates is necessary to minimize the potential risks of salinity and nutrient imbalance (Alaboz et al., 2021; Namli et al., 2023). Further studies should be designed to include multi-site and long-term research to determine cumulative soil impact, develop optimal application methods based upon different environmental conditions, and further define appropriate rates for the safe and effective application of digestate in sustainable agricultural production.

Effects of liquid digestate on macro and micro nutrient contents in wheat kernel

The findings show that the effects of biogas-derived liquid digestates on wheat kernel nutrient composition varied depending on the element considered and were influenced by digestate source and application rate. Nutrient accumulation in wheat kernels is influenced not only by external nutrient supply but also by plant physiology, nutrient translocation, and environmental conditions. The small amounts of both N and P that were found in the wheat grain samples would suggest that they are used mostly during the time period of vegetative growth and that any accumulation in the grains of the wheat plants would be limited by both genetic and environmental variables (Möller and Müller, 2012; Walsh et al., 2018; Barłóg et al., 2020). Conversely, the movement and accumulation of K appears to be more affected by the composition of the digestates suggesting that the source of the original organic feedstocks contributes to the flow of nutrients from one system to the next (Alburquerque et al., 2012; Nkoa, 2014; Bachmann et al., 2016). Fe exhibited a pronounced responsiveness to digestate applications. This can be explained by the influence of organic complexes in the digestate on the solubility of Fe and its uptake by plants (Möller and Müller, 2012; Nkoa 2014). Overall, these results indicate that digestate applications influenced nutrient accumulation in wheat kernels through element-specific mechanisms. Therefore, digestate source and chemical composition should be considered when evaluating their effects on kernel nutrient quality.

Correlation analysis among wheat yield, yield traits, kernel nutrient contents, and net income

Correlation analysis showed a highly significant positive relationship between net income and kernel yield, indicating that economic performance was primarily driven by yield formation (Figure 3). In addition, the close relationship between yield and yield traits confirms that yield formation is controlled by multiple components (Slafer et al., 2014; Sadras and Calderini, 2015). Conversely, protein and gluten traits exhibited much lower or no correlation with yield, which further demonstrates the common yield-protein trade-off that occurs due to N dilution during high yields (Triboi and Triboi-Blondel, 2002; Gooding et al., 2003). Furthermore, the variable correlations between nutrient contents and yield or quality traits indicate that nutrient accumulation is influenced by multiple interacting factors. Overall, these relationships suggest that digestate applications primarily improved yield and economic return, whereas their effects on kernel nutrient composition and quality traits were more limited and complex.

Principal component analysis (PCA) among the properties examined

PCA highlighted the integrated relationships among yield, quality traits, nutrient contents, and net income (Figure 4). Yield, yield components, and economic return were mainly associated with the first principal component, indicating that productivity was the main driver of economic performance. The second principal component was more closely associated with kernel quality traits and selected nutrient contents, suggesting that these variables were partly independent of yield. This is consistent with the previous studies that demonstrated quality traits are influenced by genetics and/or environmental issues, but are not directly linked to nutrients in every instance (Sogn et al., 2018; Barłóg et al., 2020). The distribution of treatments in

the PCA space indicated that moderate digestate application rates were associated with better yield and economic outcomes, whereas higher rates were less efficient, probably due to increased costs and potential soil-related constraints. In general, PCA indicates that use of digestate as a management practice impacts the balance of yield, quality, and/or economic returns, rather than positively impacting all of these parameters uniformly.

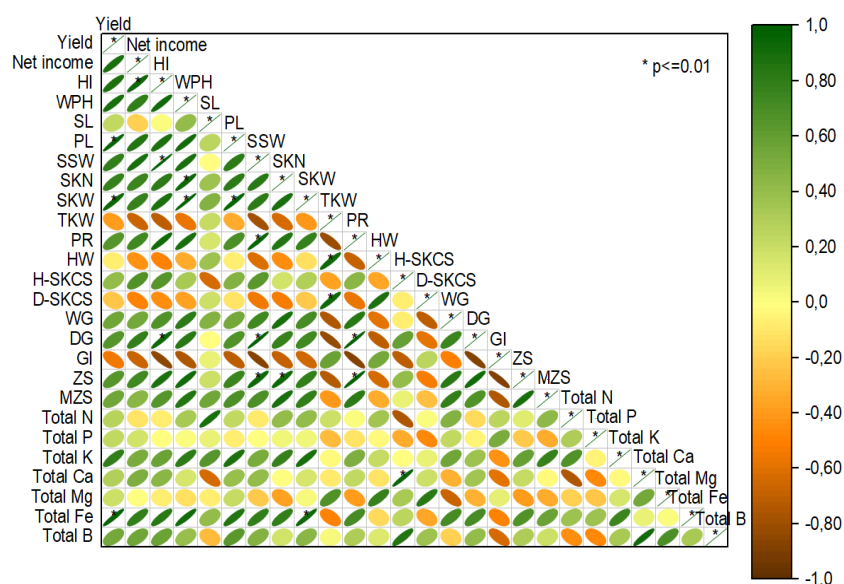


Figure 3. Correlation analysis between wheat yield, yield components, macro- and micro-nutrient contents in wheat kernels, and net income under control, mineral fertilization (NPK), and different liquid digestate doses in field conditions using digestates derived from three different biogas production facilities (HI: Harvest index, WPH: Wheat plant height, SL: Spike length, PL: Peduncle length, SSW: Stem+spikelet weight, SKN: Spikelet kernel number, SKW: Spikelet kernel weight, TKW: Thousand kernel weight, PR: Crude protein, HW: Hectoliter weight, H-SKCS: Hardness-Single Kernel Characterization System, D-SKCS: Diameter- Single Kernel Characterization System, WG: Wet gluten, DG: Dry gluten, GI: Gluten index, ZS: Zeleny sedimentation, MZS: Modified zeleny sedimentation). ** $p < 0.01$.

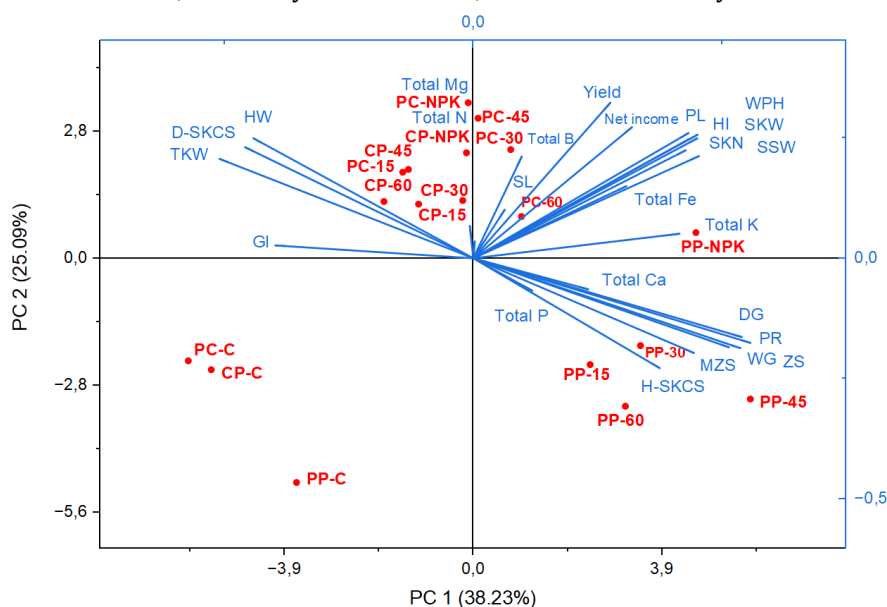


Figure 4. Principal component analysis (PCA) between wheat yield and yield components, macro-micro nutrient contents in wheat kernel and net income under control, mineral fertilization (NPK), and different liquid digestate doses in field conditions using digestates derived from three different biogas production facilities (PP: Liquid digestate from poultry waste + plant (poppy) waste, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste, NPK: Optimum fertilization, C: no-fertilization and liquid digestates, HI: Harvest index, WPH: Wheat plant height, SL: Spike length, PL: Peduncle length, SSW: Stem+spikelet weight, SKN: Spikelet kernel number, SKW: Spikelet kernel weight, TKW: Thousand kernel weight, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste, NPK: Optimum fertilization, PR: Crude protein, HW: Hectoliter weight, H-SKCS: Hardness-Single Kernel Characterization System, D-SKCS: Diameter- Single Kernel Characterization System, WG: Wet gluten, DG: Dry gluten, GI: Gluten index, ZS: Zeleny sedimentation, MZS: Modified zeleny sedimentation). ** $p < 0.01$.

Polar heatmap and dendrogram of the examined properties

The analysis of the polar heat maps and hierarchical cluster analysis allowed for a clear grouping of variables into functional clusters. The clustering of kernel yield and net income confirmed that yield was the main determinant of economic performance (Figure 5). This cluster also contained the important components of yield, indicating that they all contribute to productivity in a coordinated manner. Quality traits also formed their own cluster, which indicates that they are not completely dependent on yield, supporting the well-documented trade-off between yield and quality in wheat (Triboi and Triboi-Blondel, 2002; Gooding et al., 2003). The nutrient elements displayed intermediate clustering relationships, suggesting that the accumulation of the nutrients was affected by yield-related dilution effects as well as by element-specific uptake mechanisms. Similar findings have been reported for digestate-based fertilization, where yield improvements are generally more consistent than changes in kernel quality or nutrient composition (Möller and Müller, 2012; Nkoa, 2014; Barłóg et al., 2020). Overall, the cluster analysis suggests that liquid digestate applications primarily improved yield and profitability, whereas their effects on kernel quality and nutrient composition were more variable and context-dependent.

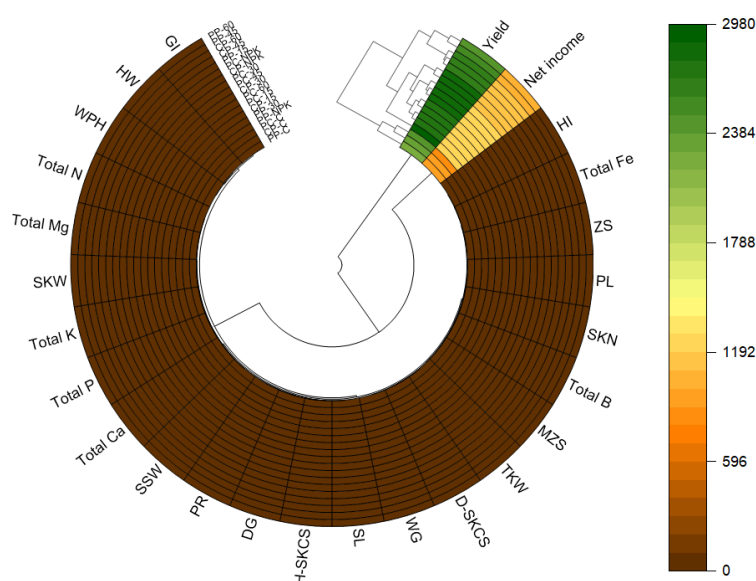


Figure 5. Polar heatmap with dendrogram between wheat yield and yield components, macro-micro nutrient contents in wheat kernel and net income under control, mineral fertilization (NPK), and different liquid digestate doses in field conditions using digestates derived from three different biogas production facilities (PP: Liquid digestate from poultry waste + plant (poppy) waste, CP: Liquid digestate from cattle waste + plant waste, PC: Liquid digestate from poultry waste + cattle waste, NPK: Optimum fertilization, C: no-optimum fertilization and liquid digestates, HI: Harvest index, WPH: Wheat plant height, SL: Spike length, PL: Peduncle length, SSW: Stem+spikelet weight, SKN: Spikelet kernel number, SKW: Spikelet kernel weight, TKW: Thousand kernel weight, PR: Crude protein, HW: Hectoliter weight, H-SKCS: Hardness-Single Kernel Characterization System, D-SKCS: Diameter- Single Kernel Characterization System, WG: Wet gluten, DG: Dry gluten, GI: Gluten index, ZS: Zeleny sedimentation, MZS: Modified zeleny sedimentation).

Economic efficiency of liquid digestate applications

Economic analysis indicated that liquid digestates have the potential to increase net returns in wheat production when applied at appropriate rates and used as partial substitutes for mineral fertilizers. Economic performance was strongly influenced by both digestate source and application rate. Moderate application rates provided a favorable yield gain-to-cost ratio, whereas higher rates reduced economic efficiency due to diminishing marginal returns. This finding agrees with previous studies showing that digestate profitability depends on the balance among nutrient availability, mineralization dynamics, and application costs (Möller and Müller, 2012; Walsh et al., 2018; Barłóg et al., 2020). Differences among digestate types can be explained by their distinct nutrient contents and physicochemical characteristics. The results indicate that digestate composition can influence its agronomic and economic efficiency as a fertilizer. The use of digestate with higher ammonium concentrations or salinity levels may negatively affect the efficiency of wheat production under specific circumstances due to their possible negative impacts (Sogn et al., 2018; Häfner et al., 2022). Therefore, digestates are an economically feasible source of fertilizer for use in wheat production, with optimal rates of application. Overall, the results also indicate that they may be used as a tool for supporting environmental sustainability and increasing profitability on farms (Tambone et al., 2009; Barłóg et al., 2020).

Conclusion

This study showed that biogas-derived liquid digestates can improve wheat kernel yield, selected yield components, and net income under semi-arid Central Anatolian conditions. The response varied according to digestate source and application rate. Moderate rates, particularly around 30 t ha⁻¹, provided the most favorable agronomic and economic outcomes, whereas higher rates tended to reduce profitability and may increase risks associated with salinity and ammonium loading. However, where long-term salinity risk and soil safety are primary concerns, 15 t ha⁻¹ may be considered a more conservative application rate. Among the digestates tested, CP and PC generally showed more consistent agronomic and economic performance than PP. Kernel quality traits and nutrient accumulation were less responsive than yield, indicating that digestate effects were more strongly related to productivity than to kernel quality improvement. However, because the study was conducted at a single location and over one growing season, the findings should be interpreted cautiously. Multi-year and multi-location studies are needed to confirm optimum application rates and to evaluate long-term effects on soil properties, nutrient cycling, environmental safety, and food quality.

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