



EVALUATION OF LIQUID DIGESTATES DERIVED FROM DIFFERENT BIOGAS FEEDSTOCKS ON PHYSICOCHEMICAL PROPERTIES AND HEAVY METAL CONTENTS OF SOIL AND WHEAT PRODUCTION UNDER CENTRAL ANATOLIAN CONDITIONS

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Abstract: This study was conducted to evaluate the effects of liquid digestates (LDs) derived from different biogas feedstocks on soil physical and chemical properties, heavy metal contents and wheat production under the semi-arid calcareous soil conditions of the Central Anatolian Region of Türkiye. The field experiment was established during the 2021–2022 wheat growing season using a randomized block design with an unfertilized control, optimum mineral fertilization (NPK), and LD applications at rates of 15, 30, 45, and 60 t ha⁻¹. Three independent field experiments with the same experimental design were established for each of the three liquid digestate types: poultry manure + poppy residues (PP), cattle manure + plant residues (CP), and a poultry manure + cattle manure mixture (PC). The chemical composition and agronomic performance of the digestates varied depending on feedstock origin. According to the obtained results, soil physical properties, including field capacity, permanent wilting point, bulk density, and saturated hydraulic conductivity, did not differ significantly among the treatments. LDs increased available P₂O₅ and K₂O contents without causing significant changes in soil pH, electrical conductivity (EC), CaCO₃, soil organic matter, available Ca and Mg, cation exchange capacity, and exchangeable cations. In PP digestate applications, available P₂O₅ increased from 52.9 to 81.7 kg ha⁻¹ and K₂O from 2477.6 to 2918.8 kg ha⁻¹. In CP digestate applications, available P₂O₅ and K₂O values ranged between 46.9–85.6 kg ha⁻¹ and 1923.0–2196.7 kg ha⁻¹, respectively. In PC digestate applications, available P₂O₅ increased from 38.8 to 89.5 kg ha⁻¹, while K₂O reached 2196.7 kg ha⁻¹. Only PP digestate significantly increased Fe and Mn contents. Heavy metal analyses revealed that Ni and Pb concentrations in the soil remained low and statistically non-significant, whereas Cd, Co, and Cr concentrations were below detection limits. Although the highest grain yields were obtained at 30 t ha⁻¹ for the PP and CP digestates and at 45 t ha⁻¹ for the PC digestate, the 15 t ha⁻¹ applications also resulted in substantial yield improvements and produced grain yields that were statistically comparable to those obtained with mineral NPK fertilization. Nevertheless, because the study was limited to short-term and single-season conditions, long-term multi-year studies are required to better evaluate the cumulative effects of repeated LD applications on soil quality, salinity dynamics, nutrient cycling, soil biology, environmental sustainability, and food safety. In addition, future studies should include pathogen, contamination, and pesticide analyses to provide a more comprehensive assessment of digestate use in agricultural systems.

Keywords: Soil physical and chemical properties, Soil fertility, Biogas feedstocks, Liquid digestate, Wheat production, Semi-arid calcareous soil conditions

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1. Introduction

The biogas sector has expanded rapidly in Türkiye during the last decade, creating important opportunities for renewable energy production and sustainable organic

waste management (IEA, 2024). Currently, approximately 95 active biogas plants operate with an installed capacity of nearly 369 MW, while the total number of biomass, biogas, and waste-to-energy facilities exceeds 180, with a combined installed capacity of about



2.4 GW (EMRA, 2024; Anonymous, 2024). Livestock manure, poultry manure, agricultural residues, food-processing wastes, municipal organic wastes, and solid wastes constitute the principal feedstocks for anaerobic digestion (EIE, 2020; FAO, 2023). These facilities process nearly one million tons of organic waste annually and contribute substantially to Türkiye's estimated biomethane production potential of approximately 7 billion m³ year⁻¹, equivalent to nearly 8% of the national natural gas demand (Ertop et al., 2023; IEA, 2024). Besides renewable energy production, anaerobic digestion generates digestate, which represents a valuable organic fertilizer supporting circular agricultural systems and contributing to soil health through nutrient recycling, organic matter inputs, and improved resource efficiency (Ertop et al., 2023; EBA, 2024). Agricultural production in the semi-arid region of Central Türkiye is constrained by low and irregular precipitation, calcareous and alkaline soils, and low soil organic matter (SOM) contents, resulting in limited nutrient availability and unstable wheat yields (Kapluhan, 2013). High calcium carbonate contents promote phosphorus fixation and reduce plant-available phosphorus (El-Damarawy et al., 2025). Although mineral fertilizers have traditionally been used to overcome these limitations, increasing fertilizer costs, dependence on fossil energy, and environmental concerns such as soil degradation and groundwater pollution have increased interest in more sustainable nutrient management strategies. Recent studies have also demonstrated that reducing mineral fertilizer inputs through the use of organic nutrient sources can improve soil quality, increase wheat yield, and enhance nutrient use efficiency (Altieri et al., 2015; Bo et al., 2025). Digestate has attracted considerable attention as an organic nutrient source within circular agriculture because it contains readily available macronutrients (N, P, K), secondary nutrients (Ca and Mg), micronutrients (Fe, Zn, Mn and Cu), and dissolved organic carbon that may enhance microbial activity, nutrient cycling, and organo-mineral interactions (Möller and Müller, 2012; Alburquerque et al., 2012; Möller, 2015; Hijazi et al., 2016; Muhmood et al., 2018). However, its agronomic performance depends strongly on feedstock composition, digestion process, soil characteristics, and application rate (Sogn et al., 2018). In particular, poultry-based liquid digestates often exhibit relatively high electrical conductivity and soluble salt contents, which may increase salinity risks under semi-arid conditions when excessive application rates are used (Tigini et al., 2016). Previous studies have demonstrated that digestates can improve cereal productivity and soil fertility under dryland conditions (Nkoa, 2014). Nevertheless, field-scale information regarding the short-term effects of different liquid digestates on wheat production, soil fertility, micronutrient dynamics, and heavy metal accumulation under the calcareous soils of Central Türkiye remains limited.

The aim of this study was to evaluate the short-term effects of liquid digestates (LDs) derived from poultry + poppy (PP), cattle + plant residues (CP), and poultry + cattle (PC), applied at rates of 15, 30, 45, and 60 t ha⁻¹, on soil physical and chemical properties, micronutrient availability, heavy metal concentrations, and wheat grain yield under the semi-arid calcareous soil conditions of Central Türkiye. In addition, correlation analysis and the multivariate statistical technique of principal component analysis (PCA) were performed to investigate the relationships among soil properties, nutrient availability, heavy metal concentrations, and wheat grain yield. The study was designed to test the following hypotheses: (H1) Liquid digestates derived from different feedstocks differ in their effects on soil fertility and wheat grain yield because of variations in their chemical composition. (H2) Wheat grain yield is expected to respond non-linearly to increasing digestate application rates, with moderate application rates providing greater agronomic benefits than higher application rates by improving nutrient availability without adversely affecting soil chemical or physical properties. (H3) Short-term application of agricultural digestates does not result in accumulation of potentially toxic heavy metals in calcareous soils. (H4) Digestates applied at appropriate rates are expected to produce wheat grain yields comparable to those obtained with mineral NPK fertilization while maintaining soil quality under semi-arid conditions.

2. Materials and Methods

2.1. Materials

2.1.1. Experiment location

The field experiment was conducted at the Sarayköy Research and Application Station of the Soil, Fertilizer and Water Resources Central Research Institute, Ankara, Türkiye, at an elevation of 894 m above sea level. The research site is located 30 km from Ankara, on the left bank of the valley stream that runs through the Mürted Plain, and west of the Ankara-Istanbul highway.

2.1.2. Climate characteristics of the research site

Figure 1 illustrates the monthly meteorological variations recorded during the 2021–2022 growing seasons in the experimental area. The climatic data indicated a typical semi-arid continental climate characterized by low and irregular precipitation, high summer temperatures, and moderate relative humidity. Precipitation was mainly concentrated during the winter and early spring months, while summer months were dry and associated with increasing temperatures. Relative humidity was higher during winter and lower in summer, whereas wind speed showed seasonal variation. Overall, the climatic conditions of the experimental area were representative of the semi-arid environments of Central Anatolia, where precipitation is a major limiting factor for agricultural production.

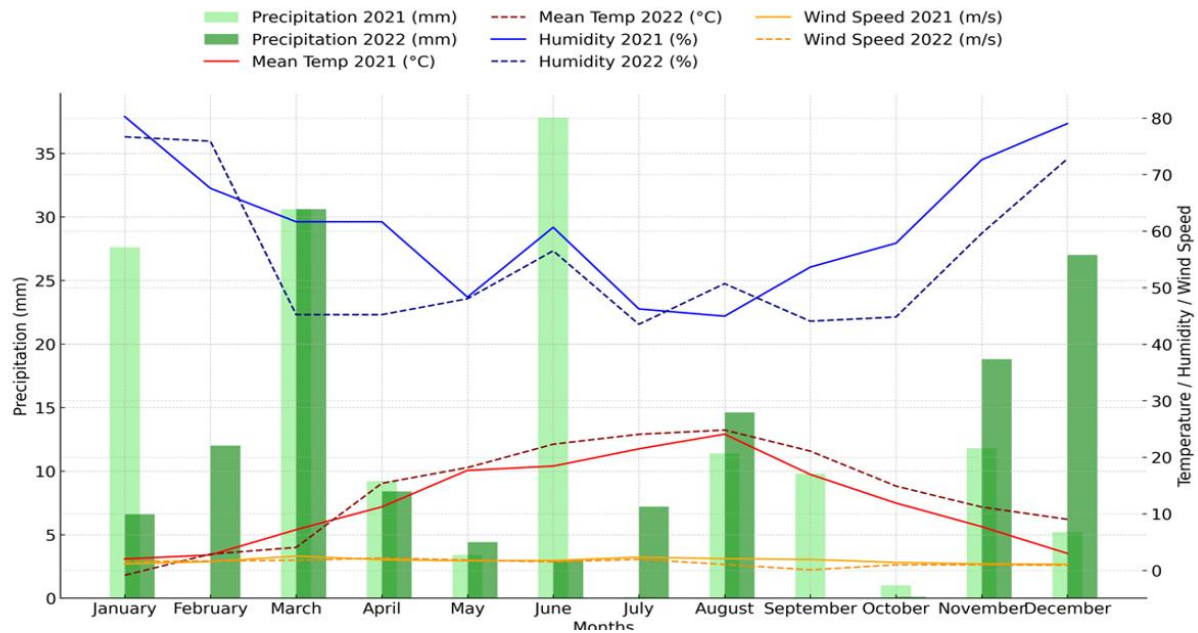


Figure 1. Monthly meteorological parameters (2021–2022).

2.1.3. Soil attributes of the experiment area

The soil properties of the experimental area are given in Table 1. The soil in the experimental area was described as having a clay (C) texture, with clay content of 44.7% for the layer at 0–20 cm depth and 48.6% for the 20–40 cm layer. This means that it has high capacity for water retention and is somewhat less permeable; characteristics typical of semi-arid soils in Central Anatolia.

2.1.4. Liquid digestates

Table 2 shows the chemical attributes of the three LDs. Physicochemical and nutrient content analysis was carried out on the LD samples using standard methods for analyzing such parameters in other related materials. Organic matter by Walkley-Black wet oxidation method (Walkley and Black, 1934). The pH and electrical conductivity were determined by the potentiometric method according to APHA (2017). Total nitrogen by Kjeldahl method (Bremner, 1996) colorimetric determination of total phosphorus after acid digestion (Murphy and Riley, 1962). Total macro and micronutrients were analyzed using ICP-OES following microwave-assisted acid digestion (USEPA, 2007).

Water-soluble P_2O_5 and K_2O were extracted with distilled water and analyzed spectrophotometrically and via flame photometry, respectively (AOAC, 2005). Total humic and fulvic acid percentages were determined using the IHSS extraction method and quantified spectrophotometrically (Swift, 1996).

2.2. Method

2.2.1. Experiment subjects and experimental design

This study consisted of three independent field experiments with the same experimental design, each established using a different liquid digestate obtained from a different biogas production plant: poultry manure

+ poppy residues (PP), cattle manure + plant residues (CP), and poultry manure + cattle manure (PC). Each experiment included six treatments (control, optimum mineral fertilization (NPK), and liquid digestate application rates of 15, 30, 45, and 60 t ha⁻¹) arranged in a randomized complete block design with three replications, resulting in 18 plots per experiment and a total of 54 plots across the study. LDs containing poultry, cattle, and plant waste from three different biogas production plants with different LD contents were obtained. The PP-digestate was obtained from Türkiye, Afyon province, the CP-digestate from Aksaray province, and the PC-digestate from a private biogas facility located in the Polatlı district of Ankara province. The PP biogas plant has an installed capacity of 4.0 MW, uses 300 tons/day of chicken waste and 70 tons of poppy husks, produces 325 tons/day of fermented waste, of which 90 tons are returned to the system, resulting in 235 tons of LD leaving the plant. The CP biogas plant has an installed capacity of 5.3 MW and uses 50% cattle manure waste and 50% plant-based organic waste. The CP biogas plant has a daily waste processing capacity of 800 tons/day, producing 384 tons/day of LD. The PC biogas plant has an installed capacity of 3.0 MW and utilizes poultry and cattle waste. The PC biogas plant has a daily waste processing capacity of 600 tons/day, with an equivalent daily output of LD.

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	Sand, %	24.3	23.3
PH	7.83	7.74	Silt, %	31.0	28.1
Soil organic matter, %	1.38	0.98	Clay, %	44.7	48.6
CaCO ₃ , %	13.1	12.3	Texture class	Clay	Clay
Available P ₂ O ₅ , kg ha ⁻¹	54.0	46.0	Bulk density, g cm ⁻³	1.22	1.16
Available K ₂ O, kg ha ⁻¹	2450	1800	Field capacity, %	32.50	36.45
Exchangeable Ca (%)	78.34	79.06	Permanent wilting point, %	16.02	19.78
Exchangeable Mg (%)	15.31	14.97	Available water capacity, %	16.48	16.67
Exchangeable Na (%)	1.92	1.96	Hydraulic conductivity, cm h ⁻¹	0.65	0.61
Exchangeable K (%)	4.43	4.01	Structural stability index	41.00	39.89
Cation exchange capacity (cmolc kg ⁻¹)	37.25	36.91			
Available Fe (mg kg ⁻¹)	3.19	3.22			
Available Mn (mg kg ⁻¹)	4.87	4.51			
Available Zn (mg kg ⁻¹)	2.39	2.06			
Available Cu (mg kg ⁻¹)	2.09	2.18			
Available Ni (mg kg ⁻¹)	0.29	0.31			
Available Pb (mg kg ⁻¹)	1.57	1.55			
Available Cd (mg kg ⁻¹)	UDL	UDL			
Available Co (mg kg ⁻¹)	UDL	UDL			
Available Cr (mg kg ⁻¹)	UDL	UDL			

Table 2. Attributes of liquid digestates used in field experiment

Attributes	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	1320	1350
Total Cu, mg kg ⁻¹	25.0	14.0	10.0
Total Mn, mg kg ⁻¹	32.0	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.

After the trial area was determined and preparations for implementation were completed, parceling was carried out on October 7, 2021. LD doses obtained from three different biogas plants and having different compositions were applied to the plots on October 12, 2021, in accordance with the experimental design. The Bayraktar

2000 wheat variety, which was registered in 2000 by the Central Research Institute for Field Crops in Ankara, was sown on November 1, 2021 at the Sarayköy Research and Application Station of the Soil Fertilizer and Water Resources Research Center Institute, Kahramankazan, Ankara, Türkiye. The sowing date was selected in

accordance with the recommended winter wheat cultivation period for the region because sowing time can substantially affect crop development, dry matter accumulation, and grain yield (Liu et al., 2021). The plant material is a seed variety that is widely used in the region and has broad adaptability and resistance to root disease. For the plots receiving optimum NPK fertilization, fertilization was carried out based on the results of soil analysis and according to the data from the Turkish Fertilizer and Fertilization Guide. One-third of the nitrogen fertilizer (as ammonium sulfate) was applied at sowing, while the remaining two-thirds were applied on April 7, 2022. DAP fertilizer was used as the base fertilizer. During the growing period, weed removal and hoeing were performed. Since no diseases were observed in the plants, no pesticide application was needed. The wheat was harvested on July 7, 2022.

2.2.2. Physical and chemical soil analyses

Two ranges of depth, 0-20 cm and 20-40 cm, were used for sampling in 2021 and 2022. Soil particle size distribution (%) was analyzed using the hydrometer method of Bouyoucos (1951). Field capacity (FC, %) and permanent wilting point (PWP, %) were estimated following Hillel (1982). Bulk density (BD, g cm⁻³) was measured following Black (1965). The structural stability index (SSI) was computed from the hydrometer data in accordance with Leo (1963) (Equation 1):

$$SSI = \sum b - \sum a \quad (1)$$

Where, b is the percentage of dispersed silt + clay determined by the standard hydrometer (mechanical) analysis, and a is the percentage of silt + clay remaining in suspension without dispersion.

Saturated hydraulic conductivity (Ks, cm h⁻¹) according to US Salinity Lab. Staff (1954) was determined with a fixed-head permeameter (Equation 2):

$$K_s = \frac{Q}{A t} \left(\frac{S}{S + H} \right) \quad (2)$$

where, A = cross-sectional area of soil column (cm²); Q = effluent discharge from the soil column (cm³); t = time passed (hours); H = water head over the soil column (cm), S = length of soil column (cm).

Soil pH was measured using a pH meter, and electrical conductivity (EC) was determined using an EC meter (dS m⁻¹ at 25 °C) according to Richards (1954). Soil organic matter (SOM, %) was determined by the modified Walkley-Black method described by Rowell (1996). Available P₂O₅ (kg ha⁻¹) is determined by extraction with a solution of sodium bicarbonate 0.5 M (pH 8.5) also described by Rowell (1996) in his publication available K₂O (kg ha⁻¹) in soil determined using ammonium acetate extraction (pH 7.0) method described by Jackson (1958). Cation exchange capacity CEC (cmolc kg⁻¹) determined following Bower et al. (1952). Fe, Mn, Zn, and Cu contents (mg kg⁻¹) were determined by ICP-OES after extraction with DTPA following the method described by Rowell (1996). Available Ca and Mg (%) were estimated

according to the method suggested by Jackson (1958). Exchangeable Ca, Mg, Na, and K (%) were determined by ammonium acetate extraction as described by Jackson (1958). Calcium carbonate (CaCO₃, %) content in the soil was determined using the Scheibler calcimeter (Soil Survey Staff, 2014).

2.2.3. Wheat yield

Kernel yield (kg ha⁻¹) was determined by threshing all plants in each sub-plot, drying the kernels at 65 °C for 48 h, and converting the obtained weight to a hectare basis following ASAE (2003) and ISO (1994).

2.2.4. Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics version 25.0 (SPSS Inc., Chicago, USA). Three independent field experiments with the same experimental design were established for each of the three liquid digestate types: poultry manure + poppy residues (PP), cattle manure + plant residues (CP), and a poultry manure + cattle manure mixture (PC). Analysis of variance (ANOVA) was conducted to evaluate the effects of treatments (Table 3, 4, 5 and 6). The assumptions of normality and homogeneity of variances were verified using the Shapiro-Wilk test and Levene's test, respectively. When significant differences were detected, mean comparisons were performed using Duncan's multiple range test at the appropriate significance level. Correlation analysis was conducted to examine the relationships among the measured parameters. Principal component analysis (PCA) and correlation analysis was performed using OriginPro 2025b (OriginLab Corporation, USA).

3. Results and Discussion

3.1. Properties of Liquid Digestates

The LDs showed marked variations in chemical composition, attracted by the influence of the origin of the feedstock on nutrient and organic matter characteristics. Organic matter content varied between 1.73% and 4.60%, with the PP digestate presenting the highest concentration indicating a greater proportion of undecomposed organic constituents. Similar trends were reported by Häfner et al. (2022) whereby the feedstock type largely controls the residual organic fraction as well as its carbon-to-nitrogen ratio that in turn affects mineralization dynamics as well as fertilizer value. The content of humic and fulvic acids was highest in the PC digestate (6.10%) which shows more humification degree and organic matter stabilization. Other results presented by Slepetic et al. (2022) also confirmed more humic-fulvic acid fractions in cattle manure-based digestates with higher retention times as well as a possibility for completeness in decomposition during anaerobic digestion. The pH values of the digestates were slightly alkaline and ranged from 7.36 to 8.65, therefore falling within typical values for biogas residues (Sogn et al., 2018). EC showed significant variation (23.0–37.4 dS m⁻¹), with the highest salinity from the PP digestate. High EC in poultry-origin digestates has been noted by many

researchers (Albuquerque et al., 2012) and explained by a high concentration of soluble ions - mostly Na^+ , K^+ , and Cl^- coming from feed and bedding residues. Soil EC remained below the threshold for wheat under the conditions of the present study (Ayers and Westcot, 1985). Total N ranged from 0.56% to 0.86%. Total K ranged from 0.40% to 0.47%. The best for both was found in the PP digestate. Poultry feedstock has a high level of N and K.

The findings of this experiment are consistent with previous research by Sogn et al. (2018) and Albuquerque et al. (2012) who investigated these same nutrients in digestate produced from poultry litter. Both of these studies concluded that the poultry feedstock contained higher levels of ammonium N and readily-available soluble K than the cattle-based feedstock which was also evaluated in this experiment. The range for total P content from the feedstocks was relatively low ranging from 1.20 - 1.86% suggesting that there is little variation

in total P content of feedstocks. The water-soluble fractions for P_2O_5 and K_2O , which respectively ranged from 0.53 - 0.79% and 0.32 - 0.37%, indicate that a large portion of these nutrients are readily available for plant immobility after being applied. Fe concentrations ranged from 1320 to 1370 mg kg^{-1} , Mn from 26.20 to 39.25 mg kg^{-1} , Cu from 10.0 to 25.0 mg kg^{-1} , and Zn was either low (10.0 mg kg^{-1}) or below detection limits in some digestates. These results support the findings of Sogn et al. (2018), van Midden et al. (2023) and Ragályi et al. (2025), who reported that digestates can supply both macro- and micronutrients to soils. In addition, concentrations of potentially toxic trace elements such as Cd, Co, Cr, and Pb were very low or below detection limits. This finding is also consistent with the results of Albuquerque et al. (2012), who reported that heavy metal accumulation is generally low in digestates derived from agricultural biomass.

Table 3. Statistical evaluation of the effects of different liquid digestates on wheat yield under field conditions

Statistical parameters	PP	CP	PC
F value	7.707	3.365	3.546
p value	0.003	0.048	0.042
Significance	**	*	*
CV, %	8.72	8.73	8.84

LDs= 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, non-significant, CV= Coefficient of variation (%).

Table 4. Statistical evaluation of the effects of different liquid digestates on chemical soil attributes under field conditions

LDs	Statistical parameters	EC	pH	CaCO_3	SOM	Av. P_2O_5	Av. K_2O	Av. Ca	Av. Mg
PP	F value	0.717	1.636	0.293	0.503	9.258	10.066	1.732	2.013
	P value	0.625	0.237	0.906	0.768	0.018	0.034	0.215	0.162
	Significance	ns	ns	ns	ns	*	*	ns	ns
	CV, %	7.32	0.58	1.92	6.52	6.73	2.05	8.25	5.01
CP	F value	0.635	0.490	0.416	1.488	8.576	4.496	2.443	2.589
	P value	0.679	0.777	0.827	0.277	0.035	0.031	0.107	0.094
	Significance	ns	ns	ns	ns	*	*	ns	ns
	CV, %	7.54	0.40	1.74	9.28	3.38	7.10	6.19	8.67
PC	F value	2.487	2.175	1.822	1.090	3.394	3.755	2.524	2.491
	P value	0.103	0.138	0.196	0.422	0.041	0.036	0.100	0.103
	Significance	ns	ns	ns	ns	*	*	ns	ns
	CV, %	9.7	0.63	1.34	9.21	3.05	8.17	8.09	9.07

LDs= 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, non-significant, CV= Coefficient of variation (%). EC= electrical conductivity (dS m^{-1}), pH= soil reaction, SOM= soil organic matter (%), Av. P_2O_5 = available phosphorus (kg ha^{-1}), Av. K_2O = available potassium (kg ha^{-1}), Av. Ca= available calcium (mg kg^{-1}), Av. Mg= available magnesium (mg kg^{-1}).

Table 5. Statistical evaluation of the effects of different liquid digestates on chemical soil attributes under field conditions

LDs	Statistical parameters	Exc. Ca	Exc. Mg	Exc. Na	Exc. K	CEC	Av. Fe	Av. Mn	Av. Zn	Av. Cu	Av. Ni	Av. Pb
PP	F value	1.941	1.709	3.250	1.248	0.527	5.110	3.675	0.612	1.775	3.740	0.511
	P value	0.174	0.220	0.063	0.357	0.751	0.014	0.038	0.694	0.206	0.066	0.762
	Sig.	ns	ns	ns	ns	ns	*	*	ns	ns	ns	ns
	CV, %	9.17	8.59	4.05	2.31	6.77	9.47	2.43	5.52	6.07	7.34	7.70
CP	F value	0.671	0.865	1.009	2.371	1.010	0.806	1.028	2.071	0.965	1.422	1.014
	P value	0.655	0.536	0.461	0.115	0.460	0.571	0.451	0.153	0.483	0.297	0.458
	Sig.	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	CV, %	6.25	4.29	7.63	5.07	4.86	2.48	6.90	3.25	6.84	5.23	2.24
PC	F value	1.802	2.231	2.533	2.755	2.325	1.337	0.219	1.310	2.089	0.783	1.311
	P value	0.200	0.131	0.099	0.081	0.120	0.325	0.946	0.334	0.150	0.584	0.334
	Sig.	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	CV, %	5.40	4.08	4.33	2.94	5.11	4.34	4.64	5.74	7.71	4.33	2.03

LDs= 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, non-significant, CV= Coefficient of variation (%). Exc. Ca= exchangeable calcium (%), Exc. Mg= exchangeable magnesium (%), Exc. Na= exchangeable sodium (%), Exc. K= exchangeable potassium (%), CEC= cation exchange capacity (cmolc kg^{-1}), Av. Fe= available iron (mg kg^{-1}), Av. Mn= available manganese (mg kg^{-1}), Av. Zn= available zinc (mg kg^{-1}), Av. Cu= available copper (mg kg^{-1}), Av. Ni= available nickel (mg kg^{-1}), Av. Pb= available lead (mg kg^{-1}).

Table 6. Statistical evaluation of the effects of different liquid digestates on physical soil attributes under field conditions

LDs	Statistical parameters	FC	PWP	BD	Ks	SSI
PP	F value	0.707	0.320	0.753	0.487	0.214
	P value	0.631	0.890	0.603	0.779	0.949
	Significance	ns	ns	ns	ns	ns
	CV, %	7.56	5.84	3.33	8.48	6.62
CP	F value	1.544	1.711	0.852	0.647	1.058
	P value	0.261	0.220	0.544	0.670	0.437
	Significance	ns	ns	ns	ns	ns
	CV, %	6.62	5.12	3.16	4.96	4.75
PC	F value	0.164	0.587	2.273	0.158	1.904
	P value	0.970	0.710	0.126	0.973	0.181
	Significance	ns	ns	ns	ns	ns
	CV, %	4.00	3.68	3.96	2.61	4.98

LDs= 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, non-significant, CV= Coefficient of variation (%). FC= field capacity (%), PWP= permanent wilting point (%), BD= bulk density (g cm^{-3}), Ks= saturated hydraulic conductivity (cm h^{-1}), SSI= structural stability index.

3.2. Effects of Liquid Digestates on Soil Attributes

3.2.1. Effects of liquid digestates on chemical soil attributes

The effects of control, optimum fertilization (NPK), and LD applications on soil chemical properties are presented in Tables 7 and 8. Statistical analyses showed that EC, pH, CaCO_3 , SOM, exchangeable Ca, Mg, K, Na and CEC values were not significantly affected by PP, CP, or PC digestate applications. PP digestate applications resulted in higher EC values ($0.85\text{--}1.36 \text{ dS m}^{-1}$) than CP ($0.75\text{--}0.83 \text{ dS m}^{-1}$) and PC ($0.76\text{--}1.12 \text{ dS m}^{-1}$) digestates. However, EC values in all treatments remained below the critical salinity threshold of 2 dS m^{-1} for wheat cultivation,

indicating that no salinity risk occurred under the experimental conditions (Ayers and Westcot, 1985). Soil pH and CaCO_3 contents remained largely stable across all digestate applications, whereas slight increases were observed in soil organic matter and exchangeable Na contents. Overall, digestate applications caused only limited short-term changes in the chemical properties of the calcareous soil. The non-significant responses of pH, CaCO_3 , SOM, exchangeable Ca, Mg, K and CEC indicate that a single-season digestate application was insufficient to modify the inherent buffering capacity of the carbonate-rich soil, which is consistent with previous studies conducted under similar conditions

(Albuquerque et al., 2012; Barłóg et al., 2020). The relatively stable soil pH observed in the present study may be attributed to the buffering effect of calcareous soils together with the neutralizing properties of digestate-derived organic compounds (Sogn et al., 2018; Amlinger et al., 2020; El-Damarawy et al., 2025). In contrast, Zhu et al. (2021) reported that pig farm biogas slurry significantly reduced soil pH in saline-alkali soils, suggesting that the effects of digestate on soil pH largely depend on the initial soil properties, especially soil buffering capacity and alkalinity, as well as digestate composition. Although exchangeable Na showed a slight increasing trend, no immediate sodicity risk was detected during the experimental period, in agreement with the observations of Sogn et al. (2018). These findings indicate that short-term digestate applications maintained the chemical characteristics of the calcareous soil while increasing nutrient availability without causing measurable chemical deterioration.

3.2.2. Effects of liquid digestates on soil macronutrients

Statistical analyses showed that available P_2O_5 and K_2O contents were significantly affected in all digestate groups ($P < 0.01$), whereas available Ca and Mg values (Table 7) were statistically non-significant.

In general, LD applications resulted in marked increases

in available P_2O_5 and K_2O levels. These findings indicate the high mineralization potential of organic phosphorus present in digestates and confirm that livestock-derived residues naturally contain considerable amounts of P and K. In PP digestate treatments, available P_2O_5 increased from 52.9 kg ha⁻¹ in the control treatment to 81.7 kg ha⁻¹ at 45 t ha⁻¹. Similarly, available K_2O increased from 2477.6 to 2918.8 kg ha⁻¹. Available Ca and Mg contents ranged between 5510.0–6013.3 mg kg⁻¹ and 798.5–944.3 mg kg⁻¹, respectively, although these differences were statistically non-significant. Nevertheless, the increasing tendency observed particularly in Mg values suggests that PP digestate may contribute as a secondary nutrient source. These increases may be explained by the mineralization of organic phosphorus and potassium compounds present in poultry-based digestates. The marked increase in available P_2O_5 and K_2O reflected the nutrient composition of the digestates and agrees with previous reports (Tambone et al., 2010). Tambone et al. (2010) reported that digestate-derived organic acids and microbial activity can increase phosphorus solubility, particularly in calcareous soils. In contrast, mineral NPK fertilizer supplied phosphorus and potassium in immediately available forms but did not contribute to the long-term enrichment of the SOM pool.

Table 7a. Effect of control, optimum fertilization (NPK) and liquid digestates on wheat yield and chemical soil attributes in field experiment

LDs	Applications	Yield	EC	pH	CaCO ₃	SOM	Av. P ₂ O ₅	Av. K ₂ O
PP	Control	2195.2 c	0.85	7.87	13.0	1.35	52.9 d	2477.6 b
	NPK	2977.1 a	0.92	7.87	13.2	1.36	57.5 c	2396.5 b
	15 t ha ⁻¹	2601.7 abc	0.87	7.89	13.2	1.37	61.6 b	2414.3 b
	30 t ha ⁻¹	2717.9 ab	1.36	7.87	13.2	1.41	60.9 b	2420.5 b
	45 t ha ⁻¹	2491.2 bc	0.91	7.81	13.1	1.58	81.7 a	2918.8 a
	60 t ha ⁻¹	2429.2 bc	0.96	7.82	13.0	1.36	74.6 ab	2389.5 b
CP	Control	2352.2 b	0.77	7.92	13.0	1.06	46.9 d	1923.0 b
	NPK	2807.9 a	0.80	7.90	13.0	1.10	52.6 c	2000.3 b
	15 t ha ⁻¹	2696.7 a	0.83	7.90	13.0	1.17	52.7 c	2011.9 b
	30 t ha ⁻¹	2850.9 a	0.79	7.91	13.1	1.19	70.7 b	2196.7 a
	45 t ha ⁻¹	2613.1 ab	0.75	7.93	13.1	1.20	85.6 a	2164.1 a
	60 t ha ⁻¹	2643.6 ab	0.80	7.91	13.2	1.18	79.3 a	2119.9 a
PC	Control	2393.7 b	0.76	7.94	13.1	1.03	38.8 c	1924.2 b
	NPK	2855.9 a	1.12	7.84	13.2	1.12	53.7 bc	1899.2 b
	15 t ha ⁻¹	2755.9 a	0.79	7.90	13.2	1.15	56.3 bc	1940.7 b
	30 t ha ⁻¹	2807.0 a	0.80	7.93	13.3	1.16	63.2 b	2013.2 ab
	45 t ha ⁻¹	2837.2 a	0.87	7.92	13.1	1.14	59.0 bc	1981.9 ab
	60 t ha ⁻¹	2775.8 a	0.78	7.95	12.9	1.17	89.5 a	2196.7 a

LDs= 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, EC= electrical conductivity (dS m⁻¹), pH= soil reaction, SOM= soil organic matter (%), Av. P₂O₅= available phosphorus (kg ha⁻¹), Av. K₂O= available potassium (kg ha⁻¹), Av. Ca= available calcium (mg kg⁻¹), Av. Mg= available magnesium (mg kg⁻¹), Exc. Ca= exchangeable calcium (%), Exc. Mg= exchangeable magnesium (%), Exc. Na= exchangeable sodium (%), Exc. K= exchangeable potassium (%), CEC= cation exchange capacity (cmolc kg⁻¹). Numbers followed by different lowercase letters within rows indicate significant differences among treatments according to Duncan's new multiple range test. ns= not significant.

Table 7b. Effect of control, optimum fertilization (NPK) and liquid digestates on wheat yield and chemical soil attributes in field experiment

LDs	Applications	Av. Ca	Av. Mg	Exc. Ca	Exc. Mg	Exc. Na	Exc. K	CEC
PP	Control	5831.7	859.2	79.03	14.50	1.94	4.66	38.63
	NPK	5656.7	798.5	75.24	18.25	1.94	4.66	39.23
	15 t ha ⁻¹	6013.3	944.3	71.29	21.80	2.02	4.75	37.10
	30 t ha ⁻¹	5680.0	820.8	83.93	9.91	2.00	4.53	39.69
	45 t ha ⁻¹	5510.0	805.5	83.28	8.80	2.00	5.91	36.60
	60 t ha ⁻¹	5905.0	860.7	76.07	16.98	2.04	4.90	37.80
CP	Control	5503.3	819.8	82.19	11.56	1.94	4.18	36.00
	NPK	5923.3	833.5	77.29	16.64	1.94	4.06	37.34
	15 t ha ⁻¹	6208.3	961.5	75.87	18.74	2.00	3.60	38.83
	30 t ha ⁻¹	5646.7	887.8	81.02	12.52	2.06	4.47	36.33
	45 t ha ⁻¹	5695.0	848.5	79.49	14.27	2.13	4.20	37.97
	60 t ha ⁻¹	5735.0	866.3	78.10	15.59	2.09	4.32	36.81
PC	Control	6163.3	929.8	75.06	19.01	1.94	3.84	37.45
	NPK	5621.7	863.8	72.22	22.67	1.97	3.36	40.79
	15 t ha ⁻¹	5445.0	852.5	79.18	15.07	1.99	3.82	37.99
	30 t ha ⁻¹	5636.7	841.5	75.21	18.76	2.04	3.92	39.92
	45 t ha ⁻¹	6085.0	949.3	74.40	19.39	2.06	4.06	38.09
	60 t ha ⁻¹	6303.3	994.7	79.48	13.65	2.11	4.60	36.84

LDs= 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, EC= electrical conductivity (dS m⁻¹), pH= soil reaction, SOM= soil organic matter (%), Av. P₂O₅= available phosphorus (kg ha⁻¹), Av. K₂O= available potassium (kg ha⁻¹), Av. Ca= available calcium (mg kg⁻¹), Av. Mg= available magnesium (mg kg⁻¹), Exc. Ca= exchangeable calcium (%), Exc. Mg= exchangeable magnesium (%), Exc. Na= exchangeable sodium (%), Exc. K= exchangeable potassium (%), CEC= cation exchange capacity (cmolc kg⁻¹). Numbers followed by different lowercase letters within rows indicate significant differences among treatments according to Duncan's new multiple range test. ns= not significant.

In CP digestate applications, available P₂O₅ values ranged between 46.9 and 85.6 kg ha⁻¹, while K₂O values varied from 1923.0 to 2196.7 kg ha⁻¹. The highest P₂O₅ concentration was observed at 45 t ha⁻¹. Available Ca values ranged between 5503.3 and 6208.3 mg kg⁻¹ and, although statistically non-significant, indicated an increase in secondary nutrient availability under cattle-based digestate applications. Available Mg values ranged from 819.8 to 961.5 mg kg⁻¹, reaching the highest value at 15 t ha⁻¹. These findings suggest that cattle-based digestates support secondary nutrient supply due to their balanced nutrient composition. Moreover, Mg may contribute to maintaining soil structure and cation exchange capacity, which are particularly important for water and nutrient retention under semi-arid conditions. In PC digestate treatments, available P₂O₅ increased from 38.8 kg ha⁻¹ in the control treatment to 89.5 kg ha⁻¹, representing the highest phosphorus concentration among all digestate groups. Available K₂O values also increased significantly and reached 2196.7 kg ha⁻¹. The strong increase in available P may be associated with phosphorus mobilization through humic substances and gradual mineralization processes. The mixed organic composition of PC digestate may have contributed to a more balanced and prolonged nutrient release pattern. Similarly, Zapata-Morales and Moreno-Andrade (2025) reported increased nutrient availability in calcareous soils following digestate applications. Overall, the results indicate that LDs can serve as

effective nutrient sources under semi-arid conditions, particularly by increasing available P₂O₅ and K₂O levels. In contrast, the absence of statistically significant changes in available Ca and Mg values suggests that short-term digestate applications did not substantially alter the basic cation balance of calcareous soils. These findings are consistent with previous studies reporting that short-term digestate applications can improve nutrient availability while maintaining the chemical stability of heavy-textured calcareous soils (Zapata-Morales and Moreno-Andrade, 2025).

3.2.3. Effects of liquid digestates on soil micronutrients

Among micronutrients, only available Fe and Mn values were significantly affected by PP digestate applications (P<0.01), whereas Cu and Zn remained statistically non-significant in all digestate groups (Table 8). In PP digestate treatments, available Fe increased from 3.25 mg kg⁻¹ in the control to 5.98 mg kg⁻¹ at 15 t ha⁻¹. Similarly, available Mn increased from 5.18 to 7.30 mg kg⁻¹. However, both Fe and Mn concentrations declined slightly at higher application rates, although they remained above the control levels. This non-linear response suggests that the beneficial effect of the poultry-based digestate on micronutrient availability may have reached an optimum at the 15 t ha⁻¹ application rate. Under calcareous and alkaline soil conditions, moderate additions of dissolved organic compounds and humic substances may enhance Fe and

Mn solubility through chelation, thereby increasing their DTPA-extractable fractions (Weimers et al., 2022). However, further increases in digestate application rate may not proportionally increase DTPA-extractable micronutrients because micronutrient release and complexation processes tend to approach equilibrium under alkaline conditions (Barzgar et al., 2025). Similar non-linear responses have also been reported for organic amendments applied to calcareous soils, where increasing application rates did not necessarily result in proportional increases in extractable micronutrient concentrations (Barzgar et al., 2025). Digestate-derived organic ligands can enhance micronutrient solubility and plant availability under calcareous and alkaline soil conditions through chelation and by reducing precipitation reactions (Weimers et al., 2022). Several studies have also reported that digestate applications increase the availability of micronutrients such as Fe in soils. Weimers et al. (2022) stated that LDs contain relatively high amounts of Fe, Mn, Zn, and Cu, which are essential elements for plant nutrition. Under alkaline and

calcareous soil conditions, the increased bioavailability of Fe may be associated with the organic matter content and chelating properties of digestates, which enhance micronutrient solubility and reduce precipitation reactions.

In CP digestate applications, numerical increases were observed in available Fe and Mn; however, these changes were not statistically significant, while Zn and Cu concentrations remained largely stable. Similarly, PC digestate applications resulted in only slight increases in Fe, Mn, Zn, and Cu concentrations, none of which were statistically significant. These findings are consistent with those of Zapata-Morales and Moreno-Andrade (2025), who reported that digestate-derived organic matter can enhance micronutrient availability in calcareous soils, although its effectiveness depends on the feedstock type and application rate. Overall, the observed increases in Fe and Mn should be interpreted as short-term responses under the experimental conditions rather than evidence of a long-term improvement in soil fertility.

Table 8. Effect of control, optimum fertilization (NPK) and liquid digestates on chemical soil attributes field experiment

LDs	Applications	Av. Fe	Av. Mn	Av. Zn	Av. Cu	Av. Ni	Av. Pb	Av. Cd	Av. Co	Av. Cr
PP	Control	3.25 ^b	5.18 ^b	1.95	2.26	0.29	1.57	UDL	UDL	UDL
	NPK	2.78 ^b	4.78 ^b	1.97	2.18	0.28	1.53	UDL	UDL	UDL
	15 t ha ⁻¹	5.98 ^a	7.30 ^a	2.01	2.45	0.37	1.62	UDL	UDL	UDL
	30 t ha ⁻¹	3.21 ^b	5.40 ^b	2.27	2.24	0.31	1.62	UDL	UDL	UDL
	45 t ha ⁻¹	2.66 ^b	5.41 ^b	2.57	2.17	0.40	1.57	UDL	UDL	UDL
	60 t ha ⁻¹	3.28 ^b	5.17 ^b	2.30	2.27	0.32	1.69	UDL	UDL	UDL
CP	Control	3.16	4.59	1.77	2.32	0.31	1.61	UDL	UDL	UDL
	NPK	3.31	5.19	2.12	2.34	0.31	1.61	UDL	UDL	UDL
	15 t ha ⁻¹	3.51	5.13	1.79	2.20	0.36	1.41	UDL	UDL	UDL
	30 t ha ⁻¹	3.48	5.13	2.17	2.42	0.33	1.61	UDL	UDL	UDL
	45 t ha ⁻¹	3.46	4.79	2.11	2.36	0.34	1.60	UDL	UDL	UDL
	60 t ha ⁻¹	3.89	7.78	2.05	2.45	0.63	1.27	UDL	UDL	UDL
PC	Control	3.21	5.10	2.10	2.38	0.33	1.67	UDL	UDL	UDL
	NPK	3.16	5.70	1.77	2.30	0.33	1.31	UDL	UDL	UDL
	15 t ha ⁻¹	3.52	5.29	1.99	2.40	0.39	1.56	UDL	UDL	UDL
	30 t ha ⁻¹	3.71	5.64	2.02	2.53	0.36	1.50	UDL	UDL	UDL
	45 t ha ⁻¹	3.47	5.49	1.88	2.29	0.33	1.29	UDL	UDL	UDL
	60 t ha ⁻¹	4.70	5.42	2.11	2.54	0.39	1.47	UDL	UDL	UDL

LDs= 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. Av. Fe= available iron (mg kg⁻¹), Av. Mn= available manganese (mg kg⁻¹), Av. Zn= available zinc (mg kg⁻¹), Av. Cu= available copper (mg kg⁻¹), Av. Ni= available nickel (mg kg⁻¹), Av. Pb= available lead (mg kg⁻¹), Av. Cd= available cadmium (mg kg⁻¹), Av. Co= available cobalt (mg kg⁻¹), Av. Cr= available chromium (mg kg⁻¹). Numbers followed by different lowercase letters within rows indicate significant differences among treatments according to Duncan's new multiple range test. UDL= under the detection limit.

Table 9. Effect of control, optimum fertilization (NPK) and liquid digestates on physical soil attributes field experiment

LDs	Applications	FC	PWP	BD	Ks	SSI
PP	Control	37.05	19.15	1.21	0.50	41.05
	NPK	35.00	18.50	1.23	0.57	42.45
	15 t ha ⁻¹	37.56	19.10	1.18	0.64	41.28
	30 t ha ⁻¹	36.09	18.80	1.20	0.31	41.34
	45 t ha ⁻¹	34.99	18.61	1.20	0.58	41.08
	60 t ha ⁻¹	36.77	19.11	1.17	0.49	40.69
CP	Control	37.20	19.28	1.30	0.71	42.06
	NPK	36.14	18.68	1.28	0.58	41.89
	15 t ha ⁻¹	37.51	19.32	1.29	0.68	43.10
	30 t ha ⁻¹	35.10	18.13	1.23	0.51	41.75
	45 t ha ⁻¹	33.44	17.94	1.29	0.49	40.39
	60 t ha ⁻¹	37.15	19.35	1.26	0.42	40.17
PC	Control	37.39	19.20	1.27	0.64	39.98
	NPK	37.32	19.27	1.26	0.56	42.33
	15 t ha ⁻¹	37.90	19.73	1.22	0.51	41.65
	30 t ha ⁻¹	37.23	19.09	1.27	0.51	41.35
	45 t ha ⁻¹	37.05	18.64	1.29	0.45	44.70
	60 t ha ⁻¹	38.17	19.39	1.34	0.55	42.28

LDs= 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, FC= field capacity (%), PWP= permanent wilting point (%), BD= bulk density (g cm⁻³), Ks= saturated hydraulic conductivity (cm h⁻¹), SSI= structural stability index.

Nevertheless, the results are consistent with previous studies reporting that digestate applications can enhance micronutrient availability through the addition of organic matter and nutrient inputs (Zapata-Morales and Moreno-Andrade, 2025).

3.2.4. Effects of liquid digestates on soil heavy metal content

In all digestate applications, heavy metal concentrations remained low, while Ni and Pb values were statistically non-significant; moreover, Cd, Co, and Cr concentrations remained below the detection limits in all treatments (Table 8). In PP digestate treatments, available Ni and Pb concentrations ranged between 0.28–0.40 mg kg⁻¹ and 1.53–1.69 mg kg⁻¹, respectively. In CP digestate applications, Ni ranged from 0.31 to 0.63 mg kg⁻¹, while Pb values ranged between 1.27 and 1.61 mg kg⁻¹. In PC digestate applications, Ni and Pb concentrations remained within similarly low ranges (0.33–0.39 and 1.29–1.67 mg kg⁻¹, respectively). Similar findings were reported by Bartkowiak and Piątek (2020) and Bonet-García et al. (2023), who found that agricultural digestates generally contain low levels of potentially toxic elements. Consistent with these studies, no heavy metal accumulation was observed under the experimental conditions of the present study during the single growing season. However, the long-term effects of repeated digestate applications on heavy metal accumulation require further investigation.

3.2.5. Effects of liquid digestates on physical soil attributes

Post-harvest soil physical properties, including FC, PWP, BD, and Ks were not significantly affected by LD

applications (Table 9). The absence of significant changes in soil physical properties may be attributed to the relatively short duration of the experiment and the limited cumulative organic matter input supplied by LDs under field conditions. Similarly, Albuquerque et al. (2012) reported that digestate applications improved nutrient availability but did not cause substantial short-term changes in soil physical properties. Nkoa (2014) also emphasized that improvements in soil physical quality generally require long-term organic amendments because soil aggregation and structural development are gradual processes. This finding is consistent with the results of Tambone et al. (2010), who reported that digestate-based amendments could preserve soil structural integrity under agricultural conditions. The absence of significant differences indicates that one-season digestate application did not measurably alter soil physical properties under the conditions of this study.

3.3. Effects of Liquid Digestates on Wheat Yield

All of the treatment groups of digestates significantly affected the yield of wheat (Table 7). Each of the different types of digestates provided a greater yield than the control treatment that did not receive any fertilizer. All of the digestates improved or maintained similar rates of yield compared to the NPK fertilizer. PP digestate applications increased grain yield (2429.2 - 2717.9 kg ha⁻¹) compared with the control treatment; however, yield declined at the 45 and 60 t ha⁻¹ application rates due to the higher EC and soluble salt content. This reduction was likely caused by osmotic stress, which restricted water and nutrient uptake by the plants. Nevertheless, digestate applications at appropriate rates

can improve plant nutrition and increase yield (Möller and Müller, 2012). CP digestate produced grain yields ranging from 2613.1 to 2850.9 kg ha⁻¹, demonstrating performance comparable to mineral NPK fertilizer. This may be attributed to its lower EC, balanced organic matter composition, increased available P₂O₅ and K₂O, and the balanced release of nutrients that supported plant growth and grain filling (Zapata-Morales and Moreno-Andrade, 2025). Grain yield under the PC digestate ranged from 2755.9 to 2837.2 kg ha⁻¹. All PC digestate produced significantly higher grain yields than the unfertilized control and statistically similar yields to the mineral NPK fertilization. Depel et al. (2026) reported that digestate applications induced element-specific changes in wheat kernel nutrient composition. K and Ca contents were significantly affected only by the PP digestate, whereas the other nutrients (N, P, Mg, and B) showed only limited variation. In contrast, the most pronounced response was observed for Fe, with significant differences particularly under the PC and CP digestate. These findings are consistent with previous studies reporting that liquid digestates applied at appropriate rates can achieve grain yields comparable to those obtained with mineral fertilizers (Šatvar Vrbančić et al., 2024; Atav et al., 2025).

3.4. Relationships between Physical and Chemical Attributes of Soils and Wheat Yield

3.4.1. Correlation analysis between soil attributes and wheat yield

Correlation analysis between wheat yield and the measured soil chemical and physical properties is presented in Figure 2. Wheat grain yield showed positive correlations with available P₂O₅, K₂O, Fe, Mn, EC, and CEC, whereas negative correlations were observed with soil pH and bulk density. These relationships are consistent with the treatment effects observed in this study, where digestate applications increased nutrient availability without significantly altering the inherent chemical characteristics of the calcareous soil. Positive relationships between yield and CEC agree with previous studies indicating that greater nutrient retention capacity may support crop productivity (Havlin et al., 2014; Weil and Brady, 2017). Likewise, the negative association between yield and soil pH is consistent with the reduced availability of phosphorus and micronutrients under alkaline calcareous soil conditions (Marschner, 2012).

Strong positive correlations were also observed between available Fe and Mn and between available P₂O₅ and K₂O, indicating that these nutrients responded similarly to digestate applications. These relationships are consistent with previous reports showing that organic amendments may enhance micronutrient solubility and nutrient availability through organo-mineral interactions (Havlin et al., 2014; Lehmann and Kleber, 2015). In contrast, Zn showed weaker relationships with other nutrients, suggesting that its behavior was influenced by additional soil chemical factors under the experimental conditions. Bulk density was negatively correlated with field capacity

and permanent wilting point, indicating that soils with lower bulk density retained more water. Similarly, the negative relationships between saturated hydraulic conductivity (K_s) and several micronutrients suggest that soil pore characteristics may influence nutrient distribution and movement (Hillel, 2004; Lal and Shukla, 2004; Dexter, 2004). Exchangeable cations exhibited both positive and negative correlations, reflecting competitive interactions among cations on soil exchange sites, which agrees with previous studies (Weil and Brady, 2017). Overall, the correlation analysis supports the short-term relationships observed between digestate application, nutrient availability, soil properties, and wheat productivity.

3.4.2. Principal component analysis (PCA) of soil properties and wheat yield

The PCA biplot (Figure 3) showed that the first principal component (PC1) explained 27.7% of the total variance, while the second principal component (PC2) explained an additional 17.1%, together accounting for 44.8% of the total variability in the dataset. The separation of treatments along these two principal components indicates that the differences among LD applications were primarily associated with changes in soil fertility indicators rather than soil physical properties. PCA results indicated that the PP digestate was more closely associated with EC and micronutrients, the CP digestate with macronutrients, and the PC digestate with wheat grain yield, available Ca, Mg, P₂O₅, K₂O, SOM, CEC, FC, and PWP. In particular, the close association of the CP-30 (CP digestate applied at 30 t ha⁻¹) and PC-45 (PC digestate applied at 45 t ha⁻¹) treatments with variables related to grain yield and soil fertility suggests that these treatments were associated with more favorable effects on wheat productivity and soil fertility. In contrast, the proximity of the PP-60 (PP digestate applied at 60 t ha⁻¹) treatment to the EC vector indicates that its relatively high salinity may have limited grain yield performance. Wheat grain yield was closely associated with available P₂O₅, K₂O, Fe, Mn, SOM, and CEC, indicating that improved nutrient availability contributed to increased grain yield. In contrast, soil pH and BD showed negative relationships with grain yield, suggesting that the alkaline nature of the calcareous soil and greater soil compaction may have limited nutrient availability and root development. Overall, the PCA results supported the findings of the statistical analyses, demonstrating that LD applications primarily improved nutrient availability without substantially altering the inherent physical properties of the calcareous soil. These findings are consistent with previous studies reporting that LD applications enhance soil fertility and plant nutrition (Tambone et al., 2010; Sogn et al., 2018; Weimers et al., 2022; Zapata-Morales and Moreno-Andrade, 2025).

4. Conclusion

LDs derived from different biogas feedstocks significantly increased the available P_2O_5 and K_2O in the calcareous soil, while the PP digestate also significantly increased the available Fe and Mn. However, no significant changes were observed in soil pH, EC, $CaCO_3$, SOM, available Ca and Mg, CEC, exchangeable cations, and soil physical properties. LD applications generally increased wheat grain yield compared with the unfertilized control. Although the highest grain yields were obtained at 30 t ha^{-1} for the PP and CP digestates and at 45 t ha^{-1} for the PC digestate, the 15 t ha^{-1} applications also resulted in substantial yield improvements and produced grain yields that were statistically comparable to those obtained with mineral NPK fertilization. Short-term LD applications did not result in heavy metal accumulation. Ni and Pb concentrations remained low and statistically

non-significant, whereas Cd, Co, and Cr in the soil remained below the detection limits throughout the study. Because the experiment was limited to a single growing season, long-term multi-year studies are needed to evaluate the long-term effects of repeated LD applications, particularly with respect to nutrient dynamics, salinity development, soil biological properties, contaminant fate, and food safety. Future studies should include post-harvest measurements of soil mineral nitrogen (NH_4^+-N and NO_3^--N) to enable a more comprehensive evaluation of nitrogen dynamics, nitrogen use efficiency, and the potential risk of nitrate leaching associated with repeated LD applications. Furthermore, future studies should include pathogen, contaminant analyses, and pesticide analyses to provide a more comprehensive assessment of digestate use in agricultural systems.

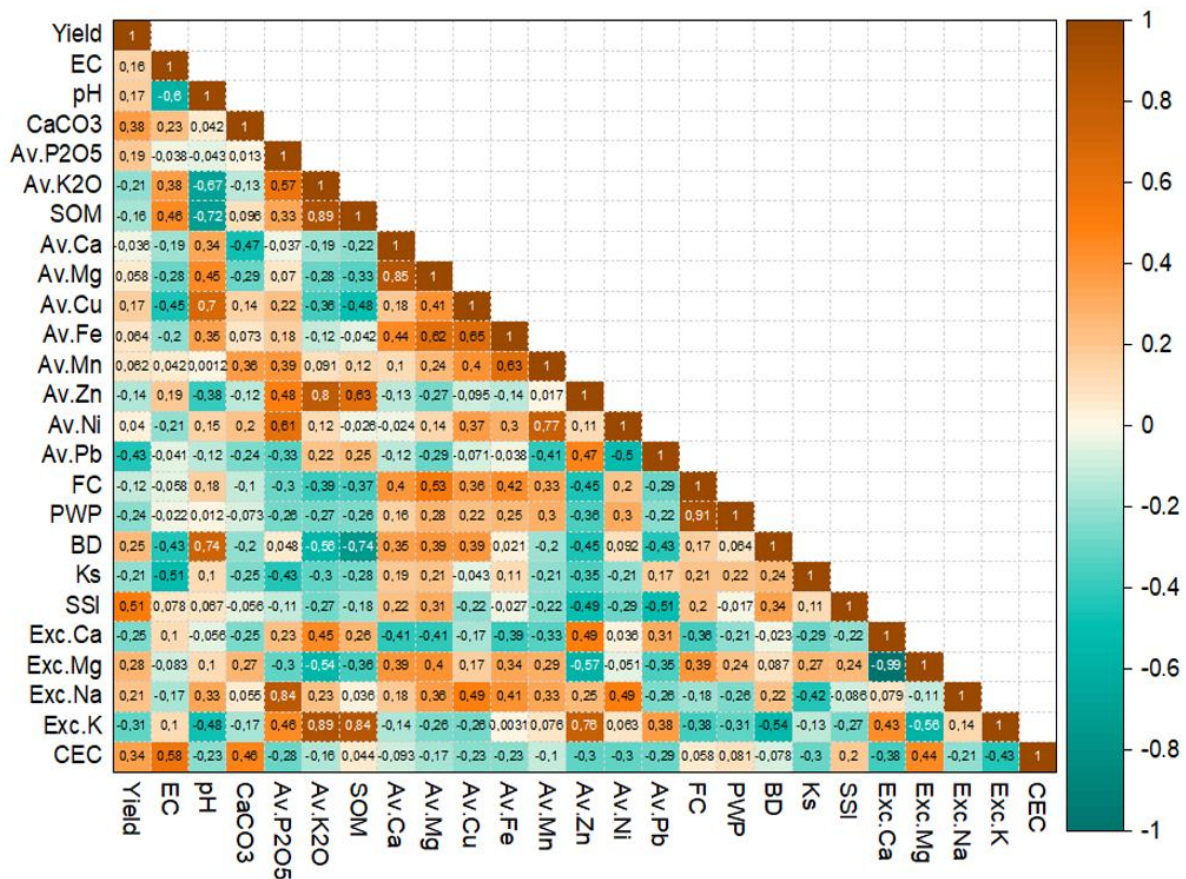


Figure 2. Correlation analysis between wheat yield, chemical and physical attributes of soils (EC= electrical conductivity (dS m^{-1}), pH= soil reaction, $CaCO_3$ (%), Av. P_2O_5 = available P_2O_5 (kg ha^{-1}), Av. K_2O = available K_2O (kg ha^{-1}), SOM= soil organic matter (%), Av. Ca= available Ca (mg kg^{-1}), Av. Mg= available Mg (mg kg^{-1}), Av. Cu= available Cu (mg kg^{-1}), Av. Fe= available Fe (mg kg^{-1}), Av. Mn= available Mn (mg kg^{-1}), Av. Zn= available Zn (mg kg^{-1}), Av. Ni= available Ni (mg kg^{-1}), Av. Pb= available Pb (mg kg^{-1}), Exc. Ca= exchangeable Ca (%), Exc. Mg= exchangeable Mg (%), Exc. Na= exchangeable Na (%), Exc. K= exchangeable K (%), CEC= cation exchange capacity (cmolc kg^{-1}), FC= field capacity (%), PWP= permanent wilting point (%), BD= bulk density (g cm^{-3}), Ks= saturated hydraulic conductivity (cm h^{-1}), SSI= structural stability index). * $P < 0.05$.

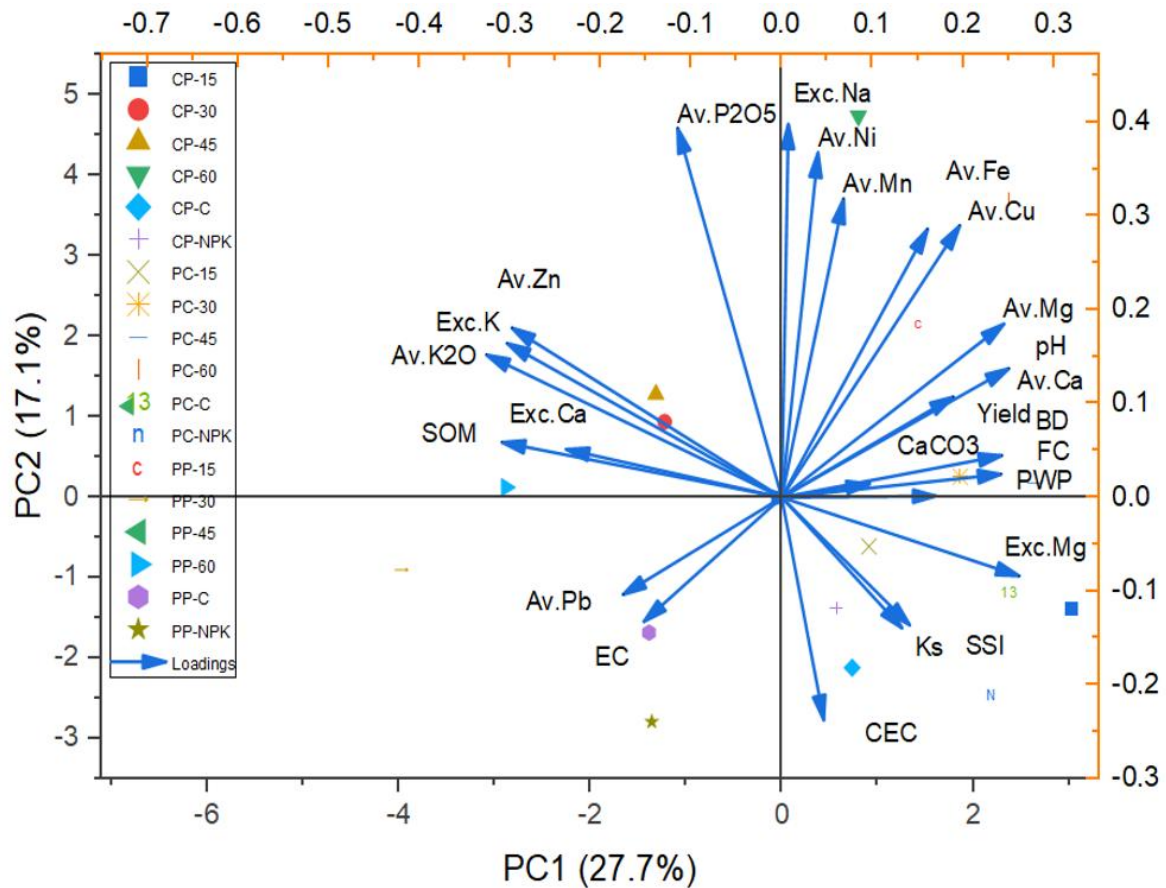


Figure 3. Principal component analysis (PCA) biplot illustrating the relationships among wheat grain yield, chemical and physical soil properties, and different liquid digestate treatments (PP= liquid digestate from poultry waste + plant (poppy) waste, CP= liquid digestate from cattle waste + plant waste, PC= liquid digestate from poultry waste + cattle waste, NPK= optimum fertilization, EC= electrical conductivity (dS m^{-1}), pH= soil reaction, CaCO_3 (%), Av. P_2O_5 = available P_2O_5 (kg ha^{-1}), Av. K_2O = available K_2O (kg ha^{-1}), SOM= soil organic matter (%), Av. Ca= available Ca (mg kg^{-1}), Av. Mg= available Mg (mg kg^{-1}), Av. Cu= available Cu (mg kg^{-1}), Av. Fe= available Fe (mg kg^{-1}), Av. Mn= available Mn (mg kg^{-1}), Av. Zn= available Zn (mg kg^{-1}), Av. Ni= available Ni (mg kg^{-1}), Av. Pb= available Pb (mg kg^{-1}), Exc. Ca= exchangeable Ca (%), Exc. Mg= exchangeable Mg (%), Exc. Na= exchangeable Na (%), Exc. K= exchangeable K (%), CEC= cation exchange capacity (cmolc kg^{-1}), FC= field capacity (%), PWP= permanent wilting point (%), BD= bulk density (g cm^{-3}), Ks= saturated hydraulic conductivity (cm h^{-1}), SSI= structural stability index).

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	G.D.	Z.D.	D.Ö.Ü.	A.N.	N.C.A.S.	Ö.D.
D	40	35		25		
DAI	35	25	15	15	10	
L	20	70	5	5		
W		100				
CR	5	80	5	5		5
SR		100				
PM	100					
FA	100					

D= design, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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